2015

Timber vs. Steel Bridge Superstructure Construction: A Simplified Structural, Economic and Environmental Analysis

Jack Dugdale
UVM College of Engineering and Mathematical Sciences, jdugdale@uvm.edu

Timber vs. Steel Bridge Superstructure Construction
A Simplified Structural, Economic and Environmental Analysis

Jack Dugdale
Advised by Eric M. Hernandez, PhD

Acknowledgements

I would like to thank Professor Eric Hernandez for his help in understanding the various nuances of the AASHTO Standards as well as his general assistance with questions regarding structural analysis and SAP modeling. I would also like to thank the rest of my thesis committee, Professors Donna Rizzo and Priyantha Wijesinghe, for their understanding and flexibility. Finally, I would like to thank my family and my friends Flora and Linnea for their support and encouragement.

Abstract

For thousands of years, bridges were constructed primarily of timber. Then, in 1779, the first cast iron bridge was built, followed by the first primarily steel bridge in 1874. By the 20th century, wood had fallen completely out of favor for all major infrastructure projects. This thesis examined if such a wholesale shift to steel is still sustainable today given increased concerns about social and environmental impacts, particularly in light of modern advances in engineered wood products. Focusing on single span highway bridges in Vermont, structural models were created to determine appropriate section sizes for functionally equivalent steel and glued laminated timber sections. Methods for performing economic and embodied energy analyses were then proposed. While final conclusions regarding the relative benefits of steel and timber were not reached, it is believed that this three-pronged approach will ultimately allow for a nuanced and multi-faceted view of the benefits and costs associated with each material, allowing for more informed infrastructure planning.

Table of Contents

1. Introduction

1.1. History

Bridges have been a critical part of civilization for as long as organized settlements have existed. Throughout the world, local cultures adapted whatever natural resources were available to construct crossings, using rope, stone and even earth in the form of bricks. Historically, however, timber was perhaps the most widely used material. The reasons for this are numerous. Firstly, outside of deserts, wood is a common and easily obtained material in most regions of the world. Secondly, it is easily worked, even with crude tools and little skill is required to achieve tolerable results, as opposed to stone or masonry. Thirdly, even without tools, a suitable, if rudimentary, bridge may be constructed by simply laying fallen logs across on obstacle. It is not surprising, therefore, that wood was frequently the material of choice for bridges. For many thousands of years this remained true. Technology improved, styles and techniques changed and advances in analysis were made, but the fundamental building blocks of wood and stone remained more or less constant.

This all changed with the coming of the Industrial Revolution and the widespread use of iron. Iron was certainly not a new discovery, having been used by the Greeks, Romans and many others. However, due to the difficulty in smelting large quantities of ore using charcoal, it had typically only been used for small objects such as pots, tools, weapons and armor. Not until the early 1700's was an efficient process for smelting iron ore using coal and later coke developed. The lower cost and higher energy density of coal when compared to charcoal allowed for cheaper mass production of cast iron. This sudden increase in supply, and associated decrease in cost, permitted the first cast iron bridge to be constructed in 1779 in Coalbrookdale, England. Subsequent advances in metallurgy resulted in the Bessemer Process, which led to the widespread development of the steel industry and the construction of the first all steel bridge in 1874 over the Mississippi River at St. Louis (Kirby et al., 1990). By the 20^{th} century, the widespread availability of high quality steel meant that timber had fallen completely out of favor as a structural material for use in bridges. To this day, steel remains a dominant construction material. Partly as a result, relatively little research has been performed regarding the advantages and disadvantages of wood as a construction material, resulting in a dearth of comprehensive information.

1.2. Reasoning

There are many very compelling reasons to utilize steel in both bridge and building construction. As an engineered product, it has carefully controlled and well known properties that the designer or engineer can use with a reasonably high degree of confidence. It is widely available in a multitude of sizes and shapes. Furthermore, steel is very strong in both tension and compression, which makes it highly adaptable for various uses. These advantages are well known and are some of the many reasons that steel has come to dominate the construction industry for large structures

However, there are also several notable disadvantages to using steel as well. First, it is comparatively heavy, having a density of 490 lbs/ft^3 (pcf) vs 140 to 150 pcf for concrete and about 35 pcf for softwood timber. For comparison, water weighs 62.4 pcf. This weight means that transportation costs and associated vehicle emissions may be significant. Second, while steel itself is not uncommon, specialized tools are required in order to cut, handle, erect and connect steel members. This can slow construction and increase project costs. Third, though steel is economically inexpensive, it can have significant environmental impacts due to high energy requirements in the mining and manufacturing processes. Finally, though it can be a durable material, steel can also experience significant corrosion when exposed to road salt, either alone or in combination with vehicle emissions. This scenario is quite common in northern regions of the United States (Houska, 2007).

Timber, in contrast to steel, is a naturally occurring material. There is thus significant variation between individual wood specimens, even from within the same tree. Knots and other defects can greatly alter the strength characteristics of the member. Additionally, the sizes of trees themselves have historically limited what could be constructed of wood. Unlike steel, which can be fabricated in any size desired, traditional timber products are directly limited by the size of the source tree. With the exhaustion of the larger old growth forests, this has restricted the commercial use of wood to dimensional lumber, the ubiquitous 2x4's and 2x6's used in home construction. While useful for many things, these small sizes are wholly unsuited to bridge construction.

However, modern technology offers a solution to both of the aforementioned issues in the form of glued laminated timber, or glulams. These are engineered wood products made by laminating together individual pieces of dimensional lumber using heat, pressure and glue to create large beams, as shown below in Figure 1. Typically, preservatives are also applied during the manufacturing stage to inhibit rot and decay.

Figure 1: Example of a glulam beam prior to finishing (Source: http://www.woodsfieldgroup.com/img/img-what.jpg)

Much like steel or concrete beams, glulam members can be made in practically any size desired, although longer lengths can present transportation and handling difficulties. Furthermore, the lamination process helps to minimize the impact of defects in individual pieces of wood. While a knot in a single 2x4 might prove critical when the member is stressed, by sandwiching that same member in amongst several other pieces of wood, the impact of that defect is minimized. As a result, glulams tend to be more dimensionally stable and have more consistent structural properties than sawn timber.

Given the adaptability of glulams, it is not surprising that they have begun to be used to construct bridges. These are typically short span bridges designed for pedestrians or light vehicular traffic, as depicted in Figure 2.

Figure 2: Glulam pedestrian bridge (Source: http://www.custompark.com/_images/products/bridges/glulam-beam-bridge-03.jpg)

However, larger designs capable of supporting normal vehicular traffic have also been constructed. As described by the American Institute for Timber Construction, an industry trade group, "[w]ood's ability to absorb impact forces created by traffic and its natural resistance to chemicals, such as those used for de-icing roadways, make it ideal for these installations" (AITC, 2007).

In addition to its structural properties, glued laminated timber also has the potential to have reduced environmental impacts in comparison to steel. Steel, for all of its beneficial properties, is energy intensive to manufacture. Even if recycled material is used (which it often is in developed countries), it still must be melted at high temperatures in order to be formed into shapes. Glulams, on the other hand, while certainly requiring more energy to produce than dimensional lumber, do not need to be subjected to processes which are as energy intensive as used in steel manufacturing. Additionally, the source material itself, wood, is renewable, unlike iron, of which there is a finite amount. The environmental impacts of the harvesting process itself depend on the techniques used, some of which are more harmful than others, but the trend in recent years has been to promote more sustainable forestry practices. Organizations such as the Forest Stewardship Council (FSC) have been created to certify forests as being sustainably managed.

While the above description speaks to the potential benefits of using glulams, relatively little research has been conducted to date specifically comparing timber and steel construction, particularly as it applies to bridges. There is therefore little concrete evidence as to whether or not either steel or glulam timber offers any concrete advantage over the other material. This paper attempts to partially address that gap.

1.3. Necessity and Hypothesis

According to an AP analysis of the 607,380 bridges included in the 2013 National Bridge Inventory, there are 65,505 structurally deficient bridges in the U.S. There are also 20,808 bridges which are fracture critical, meaning that the failure of a single member can result in complete collapse. A total of 7,795 bridges were labelled as being both structurally deficient and fracture critical. (AP, 2013) This has led the American Society of Civil Engineers to give the nation's bridges an overall grade of a C+ in its latest Report Card for America's Infrastructure. (ASCE, 2013)

There is clearly a need, therefore, for significant infrastructure improvements and the construction of numerous new bridges in the coming years. Given this, as well as the natural desire of state and federal agencies to save money wherever possible, the importance of prompt replacement of deficient bridges and the growing interest in green building practices, it would be wise to consider all available construction materials for use in such projects. However, while steel and concrete are well studied, timber has been little examined as a possible structural material for bridges. The current focus on the state of America's transportation network offers an opportune time to correct that oversight so that engineers and policymakers have accurate information on which to base decisions.

The goal of this thesis is not to demonstrate that wood is a viable structural material in general. The tens of thousands of wood frame buildings built every year, the historic post and beam structures and the miraculous engineering feats of ancient cultures leaves no doubt that it can be used quite effectively. Nor is the purpose even to show that bridges specifically can be constructed from wood. Many thousands of sophisticated bridges were made of wood in the past, and hundreds still exist to this day, spanning hundreds of feet and carrying modern traffic loads. Instead, this thesis intends to examine whether, using modern engineered wood products, a timber bridge can be *competitive* with a more typical steel girder bridge and offer a viable alternative for the construction of new infrastructure. It is theorized that timber is in fact a practical alternative to steel for bridge superstructures when all relevant factors are considered. This thesis will attempt to compare the relative merits of steel and timber in three important categories: structural properties, economic cost and environmental impact. Conclusions will then be drawn regarding in which situations, if any, wood may be an appropriate material to utilize. It is anticipated that timber will offer the most benefits, both economic and environmental, in short bridges of less than 50 feet in length. For longer spans, it is expected that the greater absolute strength of steel will permit the construction of more efficient structures with less material, reducing both cost and environmental impact.

2. Literature Review

A tremendous amount has been written about the merits and properties of steel design, as well as its economic and environmental impact. There is much less literature of note in regards to wood design in general or of bridges in particular. The most comprehensive analysis thus far was performed by the U.S. Forest Service in 1990 and primarily focuses on lightly travelled short spans used in National Parks. Furthermore, the only environmental comparisons found between wood and steel focus primarily on residential and commercial structures, as opposed to infrastructure, and vary widely in their conclusions. Therefore, a wide variety of resources were required in order to create a representative and useful knowledge base.

The structural properties of steel (AISC, 2013) and timber (NDS, 2015) have both been extensively researched and tabulated. Multiple volumes list the properties of every conceivable material and section type which one might encounter. In general, structural steel is available with yield strengths of 36 or 50 ksi (AISC, 2013). Wood, while more variable, depending on both the species and the loading orientation, typically has a design bending strength between 1.5 and 2.5 ksi (NDS, 2015).

In addition to extensive data on material properties, many specifications and codes have been developed governing the construction standards for steel bridges (FHWA, 2012) and bridges in general (AASHTO, 2012). There are fewer standards available specifically for wood bridges, but some useful information can be obtained from the experiences of the U.S. Forest Service (USFS, 1990).

An economic analysis is naturally dependent on site specific conditions. Depending on the proximity of the construction site to mills, factories, access points and other features, costs can vary significantly. Labor costs also vary by region. For this reason, it will be assumed that the bridges discussed in this study will be constructed in the vicinity of Burlington, Vermont. Price estimation will then be based primarily on the five year averaged price list published by the Vermont Agency of Transportation (VTrans) The figures found in this table provide a rough guide to construction costs based on the amount of material needed for each component, allowing the initial cost of the project to be calculated. These values, however, are based on data from projects of various sizes scattered throughout the state. Thus, while they provide a useful approximation, actual costs will likely vary significantly depending on site specific conditions.

The final element of analysis focuses on the relative environmental impact of each material choice. There are multiple ways in which this can be measured, but for this analysis, the *embodied energy* needed to produce each material will be the primary metric. (For further detail on this, please see the methodology section.) A great deal of research has been done on this subject, covering multiple materials and uses in many countries. Due to the varying inputs (distance between resource and mill, amount of recycling, energy sources used for processing, type of transportation, boundaries of study, etc.), the calculated values for each material can vary tremendously, sometimes by orders of magnitude. The data varies both between countries and regions as well as between researchers in the same country. Nonetheless, this has only encouraged further study, so there is a plethora of available information on the subject.

The single most comprehensive data set created to date, offering information on most common structural materials, is the *Inventory of Carbon and Energy* (Hammond and Jones, 2011), which contains extensive and well documented numbers for every material. Unfortunately, the study focused primarily on the UK and EU, so the data, particularly for timber, may not be fully applicable to an American analysis. Further information is available from The United Kingdom (Harris, 1999), India (Reddy and Jagadish, 2003), New Zealand (Buchanan and Honey, 2003; Alcorn and Baird, 1996) and the United States (Griffin et al., 2010). On the whole, however, the majority of papers seem to come out of Europe and New Zealand, perhaps due to more restrictive carbon emission limits. In general, all sources agree that steel has a higher embodied energy (typically around 20 MJ/kg) than wood (closer to 10 MJ/kg).

In addition to raw data focusing solely on the embodied energy of individual materials, several studies comparing materials have been conducted, primarily focusing on residential and commercial buildings. The most relevant of these is perhaps one which focuses on French single family homes built with locally sourced material versus similar homes built with concrete (Morel et al., 2010). The results of that study indicated that total energy consumption was reduced by 215% when locally sourced materials were used.

3. Methodology

3.1 Bridge Design and Analysis

In order to effectively compare the benefits of steel and timber bridge superstructure construction, it was first necessary to develop structurally equivalent bridges which could then be analyzed from an economic and environmental perspective. As the goal of this thesis was not to provide detailed construction guidelines for timber bridges, but rather a relative comparison between timber and steel, it was decided that a series of hypothetical structures would be modeled. By using conjectural designs, rather than site specific plans, a more general result could be provided. This approach also served to significantly reduce the number of potential variables, thus restricting the following analyses to only the most pertinent information. Additionally, it should be noted that only the superstructure elements, meaning the deck and primary supporting girders, were considered in this and subsequent analyses. Abutments were not examined, nor were secondary members beneath the deck, such as transverse stiffeners.

The basic design chosen as a template was a simply supported one span bridge of varying length supported by three main girders. The bridge was designed for moderate vehicular traffic and no pedestrian traffic, such as might be expected on a rural state highway. Overall width was 31 feet, giving two 11 foot travel lanes and two 3.5 foot shoulders. The center lines of the exterior girders were placed 3.5 feet from the edge of the bridge deck, resulting in a center to center beam spacing of 12 feet. Following the general practice of the Vermont Agency of Transportation, a cast in place concrete deck 8.5 inches thick was placed on top of the support girders. It was assumed for all calculations that the deck and girders experienced full composite action. A three inch thick asphalt wearing surface was assumed to be placed on top of the deck. No sidewalks were supplied, but TL-4 crash rated guardrails conforming to VTrans Standard S-352 were positioned along the deck edges. Standard plans for these guardrails have been included in Appendix D. Schematics showing the cross section of the design bridge are provided in Figures 3a and 3b.

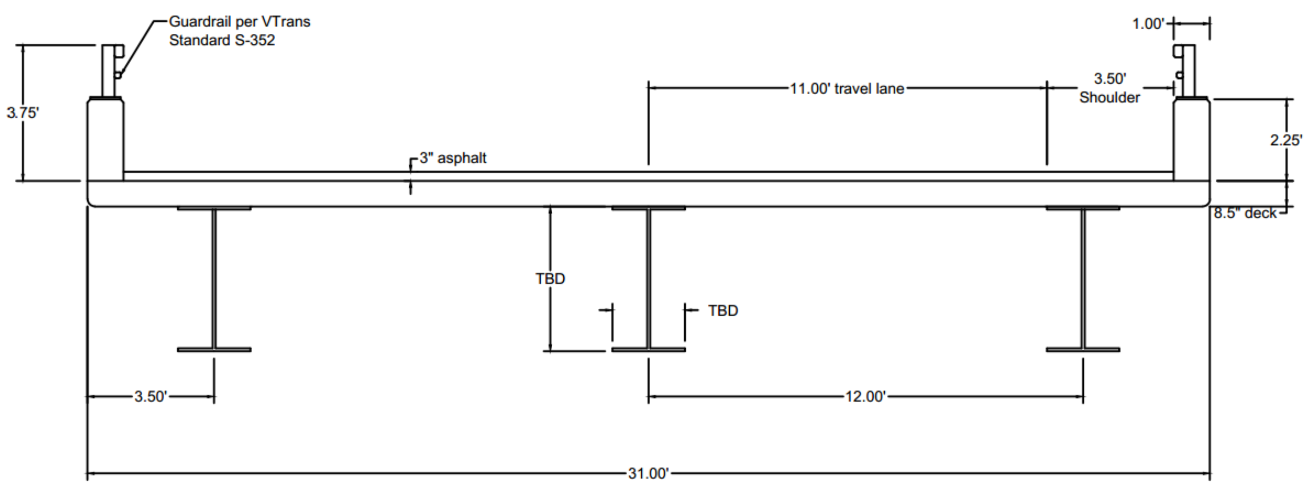


Figure 3a: Cross section of the design bridge with steel girders

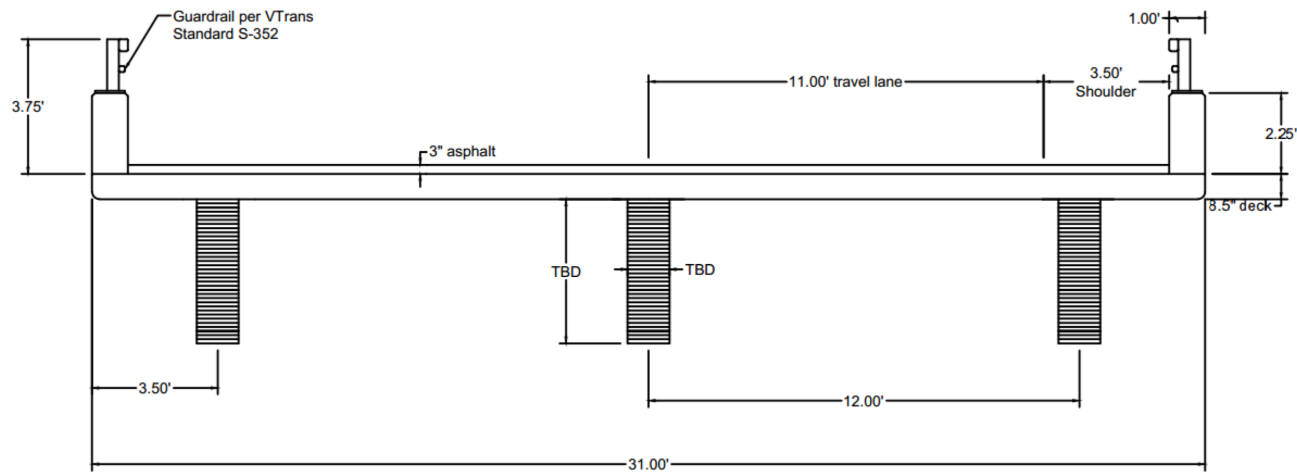


Figure 3b: Cross section of the design bridge with glulam girders

To account for a wide variety of potential bridge configurations, the design bridge was modeled in SAP2000 for nine different span lengths ranging from 20 to 100 feet, in 10 foot increments. Only the concrete deck and steel or wood girders were included as model elements. The asphalt pavement layer and guardrail were both accounted for in the form of applied dead loads. The steel sections were assumed to be made from A992 steel while the timber beams were designed using 26F-1.9E southern pine glulams. The concrete was taken to have a compressive strength of f'_c = 4000 psi. The steel and concrete sections utilized built-in properties already defined in SAP2000. However, in order to represent the glulam beams, a new material property needed to be created using the "Define" menu in the SAP workspace. This was done by idealizing the timber as an orthotropic material, meaning it has three principle, mutually perpendicular directions along which its properties varied. For wood, these are the longitudinal (parallel to the grain), tangential and radial directions. The values of the various elastic properties along these directions were obtained from a table in the 1990 Forest Service publication *Timber Bridges: Design, Construction and Maintenance* which provided ratios between the different properties for various wood species. These values were also checked against those provided in the 2010 Forest Products Laboratory *Wood Handbook*. The ratios given for loblolly pine, which is one of the species comprising the southern pine species group, were used to represent southern pine in general. According to the North Carolina State University Tree Improvement Program, "[l]oblolly pine is the most commercially important tree species in the southeastern United States, responsible for the majority of the harvested timber." It is therefore believed that the strength values used can be considered representative of southern pine in general. The material properties for steel, concrete and glulam which were used in the models are provided in Tables 1, 2 and 3, below.

Table 1: Material Properties of Steel in SAP2000 Model

Property Description	**SAP2000 Notation**	**Value**
Modulus of Elasticity (E)	E	29000 ksi
Poisson's Ratio (ν)	U	.3
Thermal Expansion Coefficient	A	6.5E-6 $°F^{-1}$
Shear Modulus (G)	G	11153.846 ksi
Minimum Yield Stress (F_y)	Fy	50 ksi
Minimum Tensile Stress (F_u)	Fu	65 ksi
Effective Yield Stress (F_{ye})	Fye	55 ksi
Effective Tensile Stress (F_{ue})	Fue	71.5 ksi
Unit Weight	Weight per Unit Volume	490 pcf
Mass Density	Mass per unit Volume	15.2297 $slugs/ft^3$

Table 2: Material Properties of Concrete in SAP2000 Model

Property Description	**SAP2000 Notation**	**Value**
Modulus of Elasticity (E)	E	3604.9965 ksi
Poisson's Ratio (ν)	U	.2
Thermal Expansion Coefficient	A	5.5E-6 $°F^{-1}$
Shear Modulus (G)	G	1502.0819 ksi
Specified Compressive Strength (f'_c)	f'c	4 ksi
Unit Weight	Weight per Unit Volume	150 pcf
Mass Density	Mass per unit Volume	4.6621 $slugs/ft^3$

Table 3: Material Properties of Southern Pine Glulam in SAP2000 Model

Property Description	**SAP2000 Notation**	**Value**
Longitudinal Modulus of Elasticity (E_L)	E1	1900 ksi
Tangential Modulus of Elasticity (E_T)	E2	214.7 ksi
Radial Modulus of Elasticity (E_R)	E3	150.1 ksi
Longitudinal-Radial Poisson's Ratio (ν_{LR})	U12	.33
Longitudinal-Tangential Poisson's Ratio (ν_{LT})	U13	.29
Radial-Tangential Poisson's Ration (ν_{RT})	U23	.38
Longitudinal Thermal Expansion Coefficient	A1	2.0E-6 $°F^{-1}$
Tangential Thermal Expansion Coefficient	A2	1.45E-5 $°F^{-1}$
Radial Thermal Expansion Coefficient	A3	1.92E-5 $°F^{-1}$
Longitudinal-Tangential Shear Modulus (G_{LT})	G12	153.9 ksi
Longitudinal-Radial Shear Modulus (G_{LR})	G13	153.9 ksi
Radial-Tangential Shear Modulus (G_{RT})	G23	24.7 ksi
Unit Weight	Weight per Unit Volume	36 pcf
Mass Density	Mass per unit Volume	1.1189 $slugs/ft^3$

The deck was modeled as a thin shell having a thickness of 8.5 inches, divided into a mesh consisting of elements six inches square. The mesh was placed at the centroid of the deck. The girders were modeled using frame elements. In order to match the resolution of the deck mesh, each girder actually consisted of a series of six-inch long segments. Vertically, these segments were placed at the centroid of the girder. To connect the girder to the deck and model the composite behavior of the bridge, fictitious joints were used. These were located every six inches along the length of the girder, connecting the nodes of the beam elements with the nodes of the shell representing the deck. The mass and weight of these elements were set to zero, while the moment of inertia was multiplied by a factor of 1000 to increase their stiffness. Doing this ensured that the forces developed in the concrete deck were fully transferred to the supporting girders. Figure 4 shows an example of the full model, while Figure 5 is a detail of one of the SAP models showing the interaction between the deck, shell and girder elements.

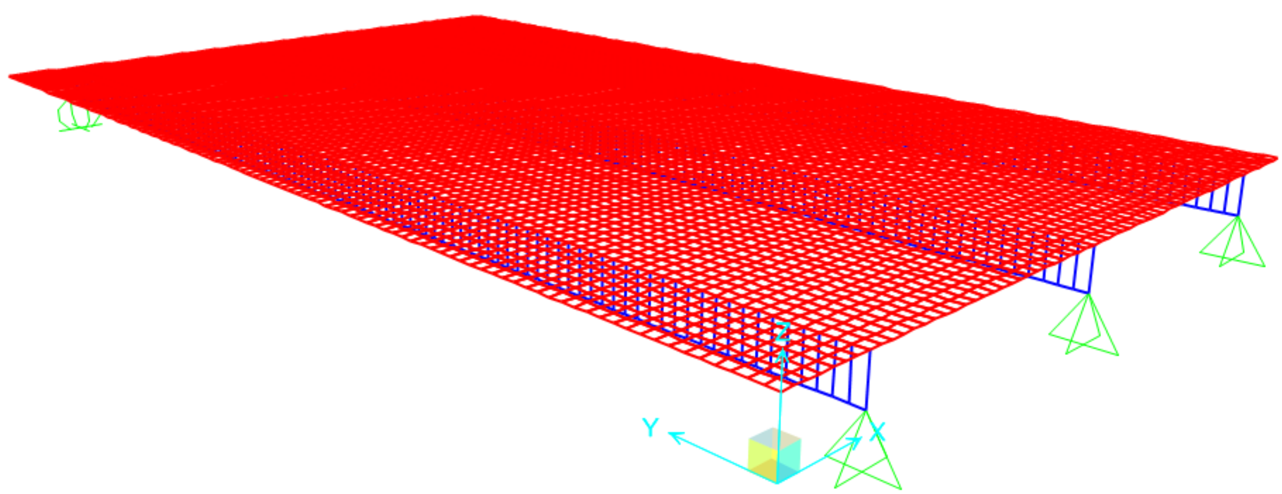


Figure 4: Perspective view of bridge model in SAP2000

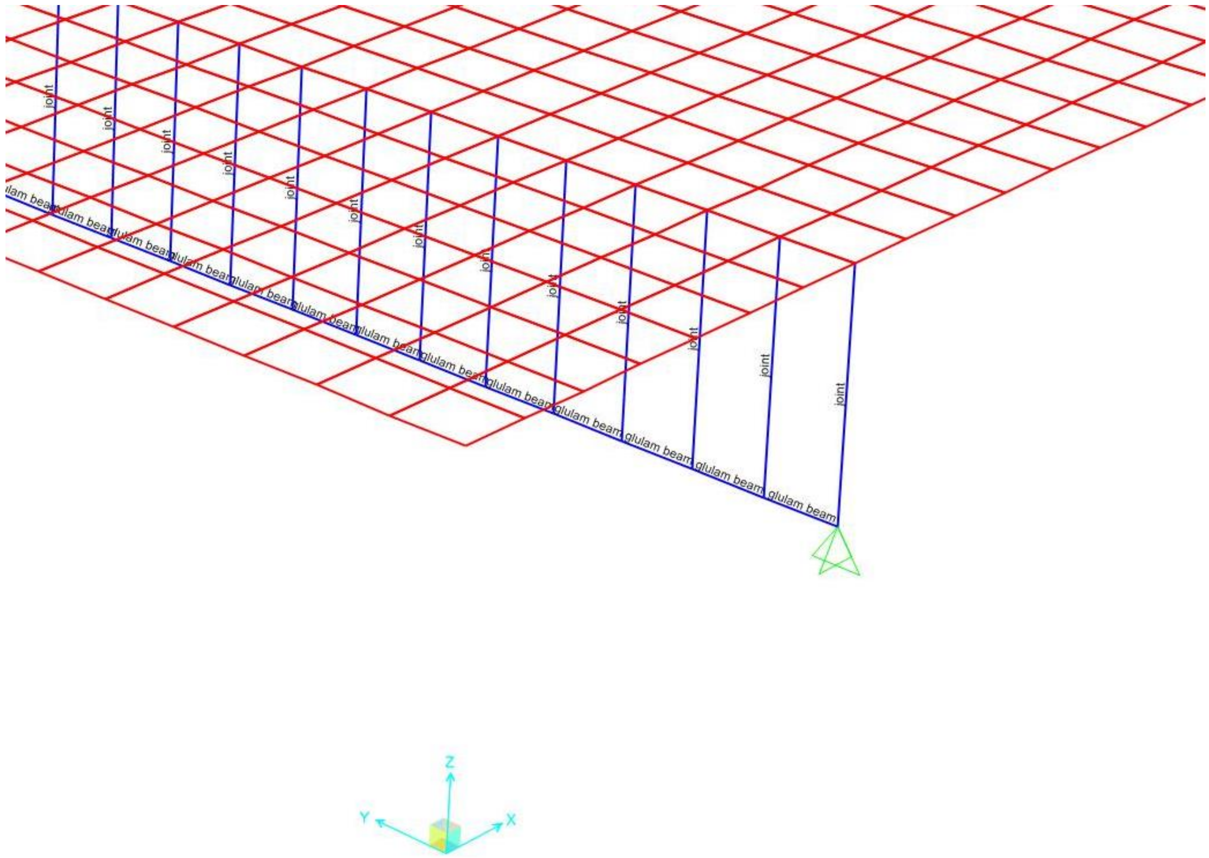


Figure 5: Detail of model showing the deck, girder and fictitious joints

The design of the structural elements of the bridge, namely the girders, followed the requirements of the 2012 *AASHTO LRFD Bridge Design Specifications*. For the purposes of this analysis, only the Strength I limit state was considered. This limit state includes the effects of the live and dead load but does not consider wind. The live load on the bridge was determined using the HL-93 load specified in Section 3.6.1.2. This dictates that two different vehicular loads be analyzed. The first is the HS20-44 truck. This consists of a three axle truck, with the front axle carrying eight kips and the middle and rear axles each carrying 32 kips. The front and middle axles are separated by 14 feet, while the distance between the middle and rear axles is permitted to vary between 14 and 30 feet so as to produce the worst effect. The second design vehicle which must be analyzed is the design tandem. This is a vehicle with two axles separated by four feet longitudinally, with both axles supporting 25 kips. Both of these design vehicles are to be applied to the bridge concurrently with a uniform load equal to 640 lbs/ft longitudinally, which is distributed across a 10 foot transverse width. These loads must be located on the bridge so as to produce the maximum possible effect.

In order to determine the design vehicle and longitudinal location which produced this effect, a series of MATLAB codes were developed. These were used to calculate the moment created in a simply supported beam by every possible position of both the design truck and the design tandem. The code may be found in Appendix A, while the results obtained are included below in Table 4. The governing load cases producing the maximum moment have been identified in bold.

Table 4: Governing Load Cases

	HS20-44 Truck Load			**Tandem Load**	
Length (ft)	**Moment (ft-kip)**	**Front Axle Position (ft)**	**Total Length (ft)**	**Moment (ft-kip)**	**Front Axle Position (ft)**
20	160	24	28	**202.5**	**11**
30	282.1333	32.5	28	**326.66667**	**16**
40	449.8	36.33333	28	**451.25**	**21**
50	**627.84**	**41.33333**	**28**	576	26
60	**806.533**	**46.35**	**28**	700.83333	33
70	**985.6**	**51.33333**	**28**	825.71424	35.99167
80	**1164.9**	**56.33333**	**28**	950.625	41
90	**1344.209**	**61.35**	**28**	1075.55521	45.975
100	**1523.92**	**66.33333**	**28**	1200.5	51

It can be seen that for span lengths over 40 feet, the HS20-44 truck will be the governing vehicle.

Once the longitudinal positioning of the load was calculated, it was next necessary to position the loads transversely to create the largest impact. By observation, it was determined that the exterior girder would be subjected to the greatest force if both the lane load and design vehicle were placed as close to the edge of the deck as permitted by AASHTO. Similarly the center girder would experience the largest moment when two trucks and two lane loadings were placed as close to it as allowed. Thus, these were the loads applied to the SAP model. The lane loads were simply created using an area load of 64 psf across a 10 foot width and along the entire length of the bridge. The wheel loads from the design vehicles were slightly more complex. According to AASHTO, each axle of the design vehicle produces two wheel loads equal to half of the axle load. This wheel load is to be distributed over an area 20 inches wide (transversely) and 10 inches long (longitudinally) to represent the contact area of the tires (200 square inches). However, due to the six inch grid spacing adopted for the bridge deck, it proved impossible to precisely meet that specification. Instead, the wheel loads were applied to an area 18 inches wide and 12 inches long (216 square inches). It was felt that this slight discrepancy in contact area would result in negligible differences in results. Additionally, it should be noted that the AASHTO specified load is applied at the surface of the deck, while the load applied in the model was located at the deck centroid, 4.25 inches beneath the surface (if the thickness of the asphalt layer is neglected). If the applied surface load is transmitted through the deck along a 45 degree shear plane, than at centroid of the deck, it will actually be distributed over an area 28 inches wide and 18 inches long, or 504 square inches. The use of a 216 square inch wheel contact area may thus be conservative at the centroid of the deck.

For similar reasons regarding the grid spacing, the axle locations specified in Table 1 could not be exactly replicated in the model. The tabulated positions were thus rounded to the nearest half foot in the model, which has the effect of shifting the load centroid closer to the middle of the span by approximately two inches. However, this may compensate for a slight discrepancy between the code used to determine the axle locations and the AASHTO specifications. The MATLAB code used to calculate axle positions only accounted for the effect of the design truck or tandem. Due to computational limits, it was not feasible to account for the simultaneous application of the truck and lane loads as specified in AASHTO. It is known, however, that the maximum moment produced by the lane load would occur at midspan. This would have the effect of shifting the total resultant moment from both the truck and the lane load closer to the middle of the bridge, which is precisely what happens when the axle positions specified in Table 4 are rounded to the nearest six inches. It is unlikely that this slight shift in location fully compensates for the effect of superpositioning the loads. However, given the excess moment capacity observed in the results, it is not believed that this slight discrepancy would have resulted in the selection of different sections. Figures 6 – 10, provided below, show the various load patterns applied to the bridges. The particular example shown is the 50 foot model with the HS20-44 three axle truck loading, but the other arrangements were fundamentally similar in appearance.

Figure 6: Dead load from railings (326.5 psf, purple) and asphalt (36.25 psf, blue)

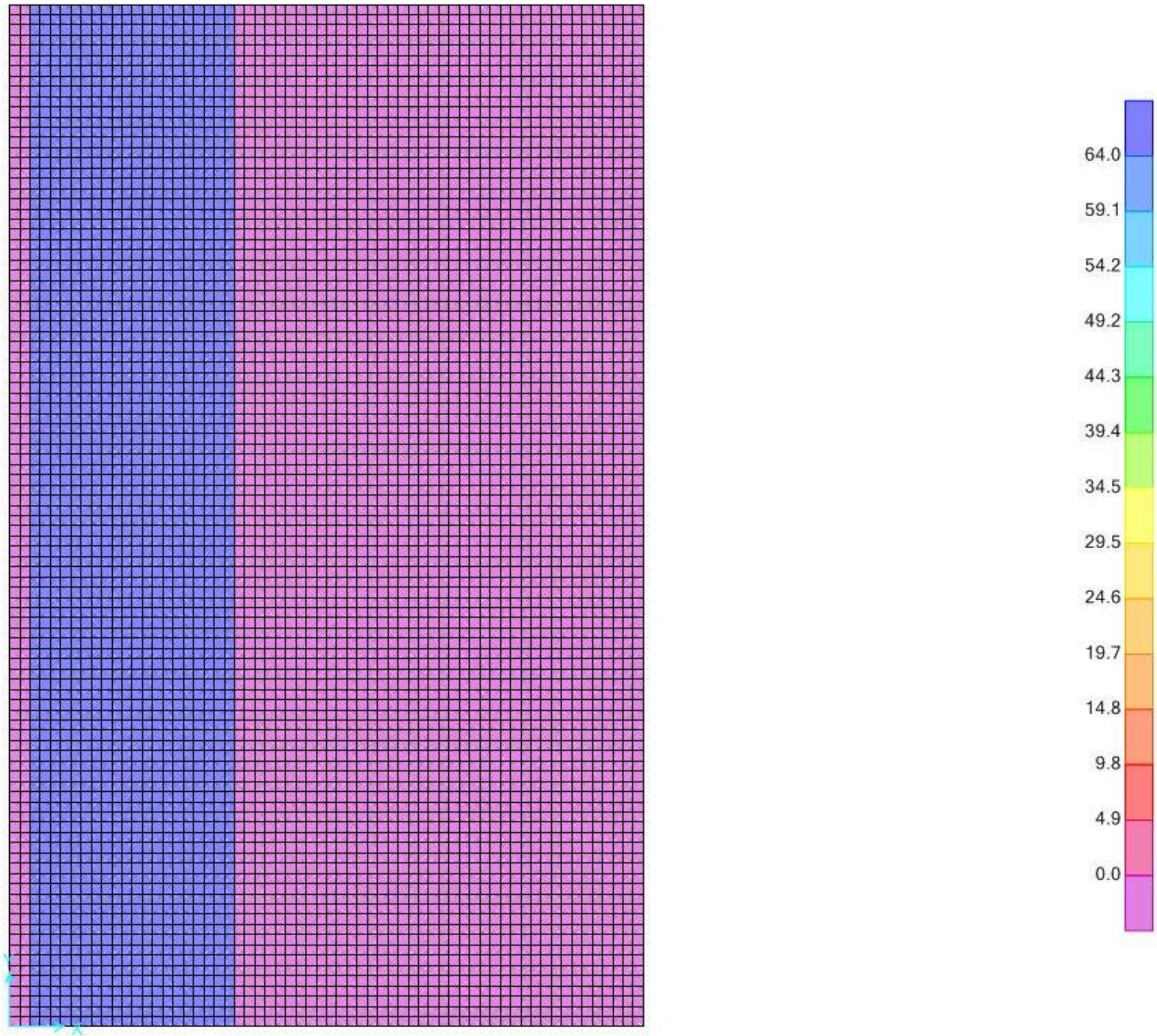


Figure 7: Lane load over the exterior girder shown in blue, 64 psf

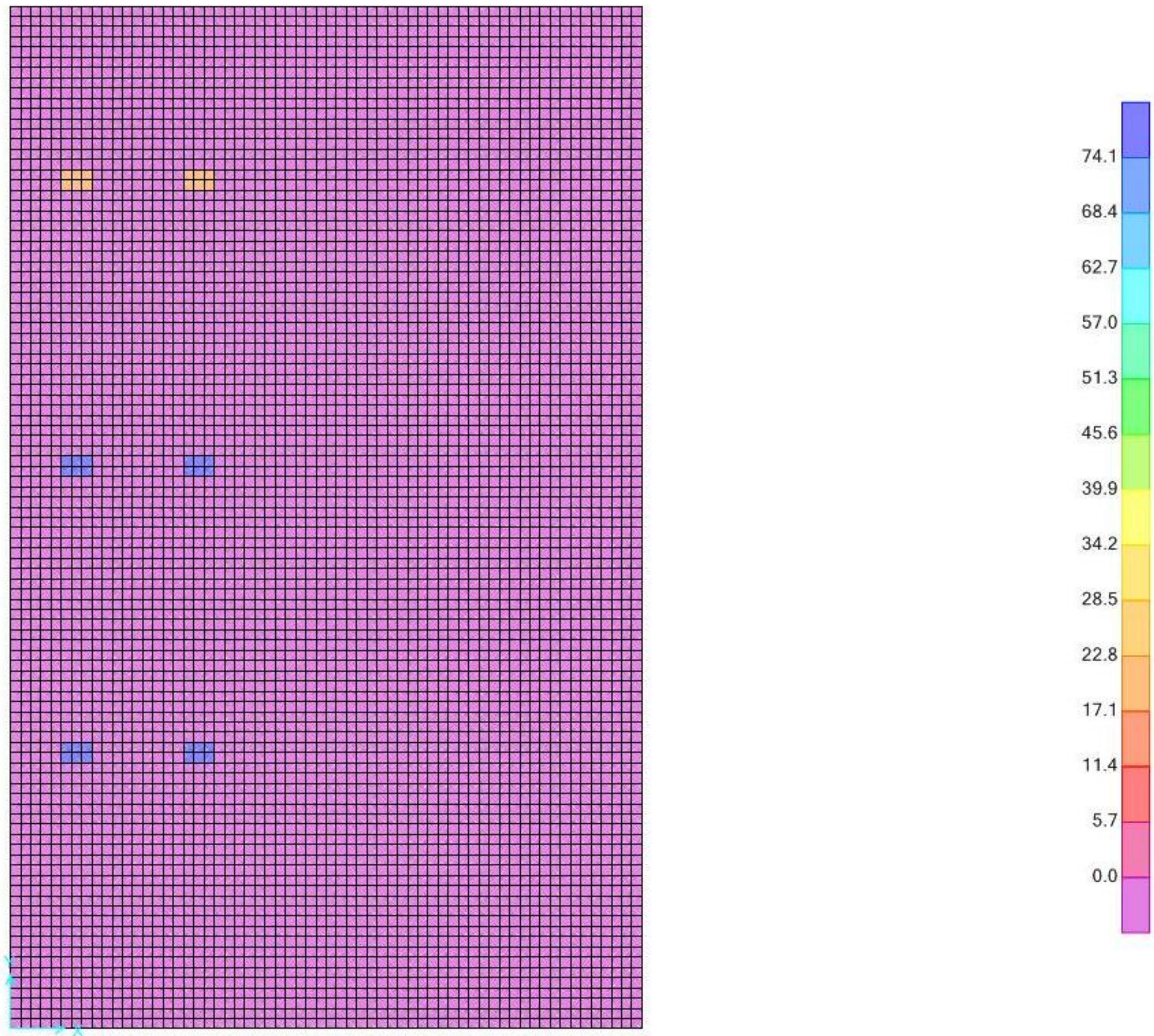


Figure 8: HS20-44 loading over the exterior girder (18.519 psi for the front two wheel loads, shown in yellow, 74.074 psi for the remaining four, shown in blue)

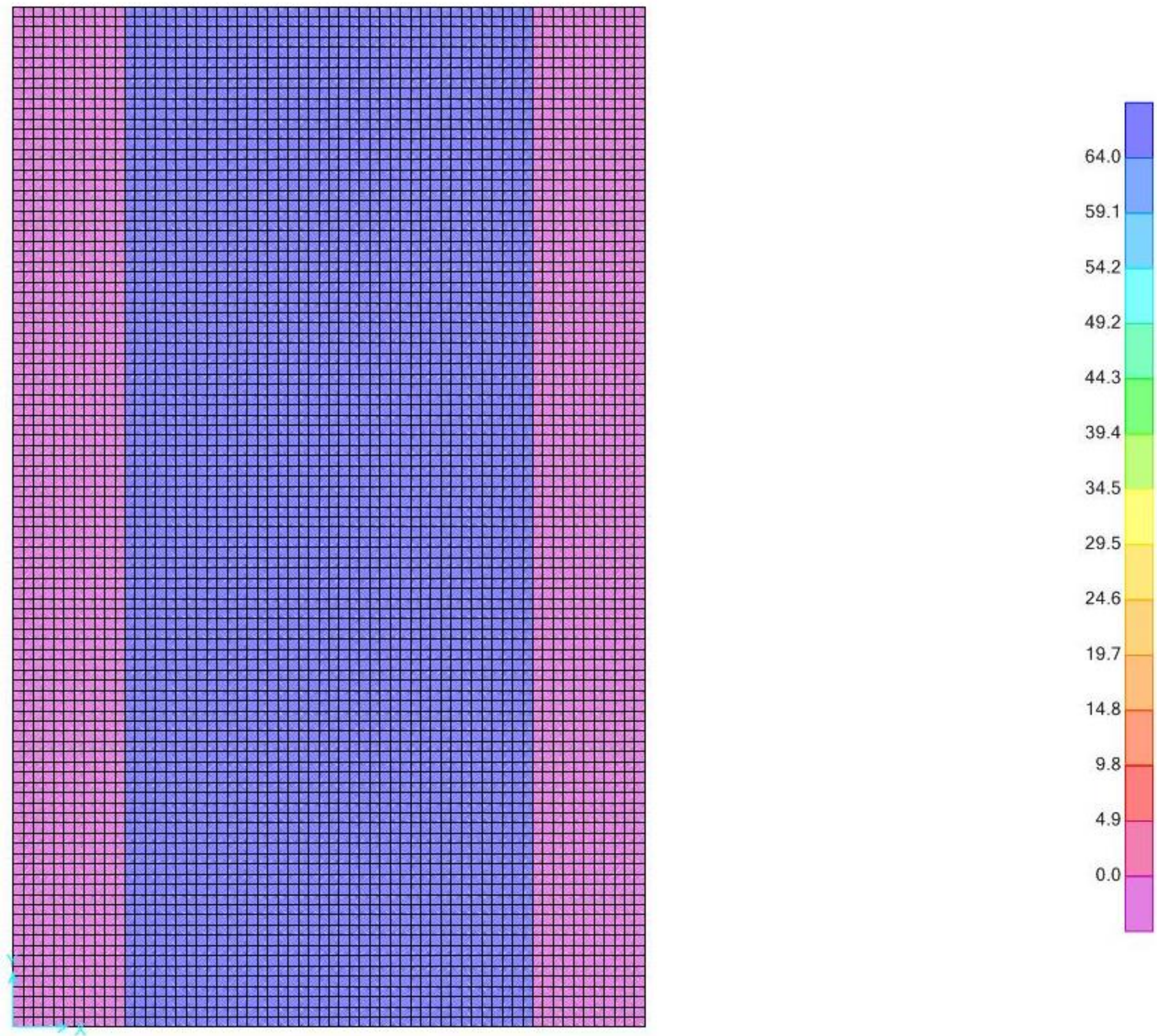


Figure 9: Lane load over the center girder (64 psf, blue). In this case there are actually two 10 foot wide lane loads adjoining each other, as permitted by AASHTO to produce the maximum load effect

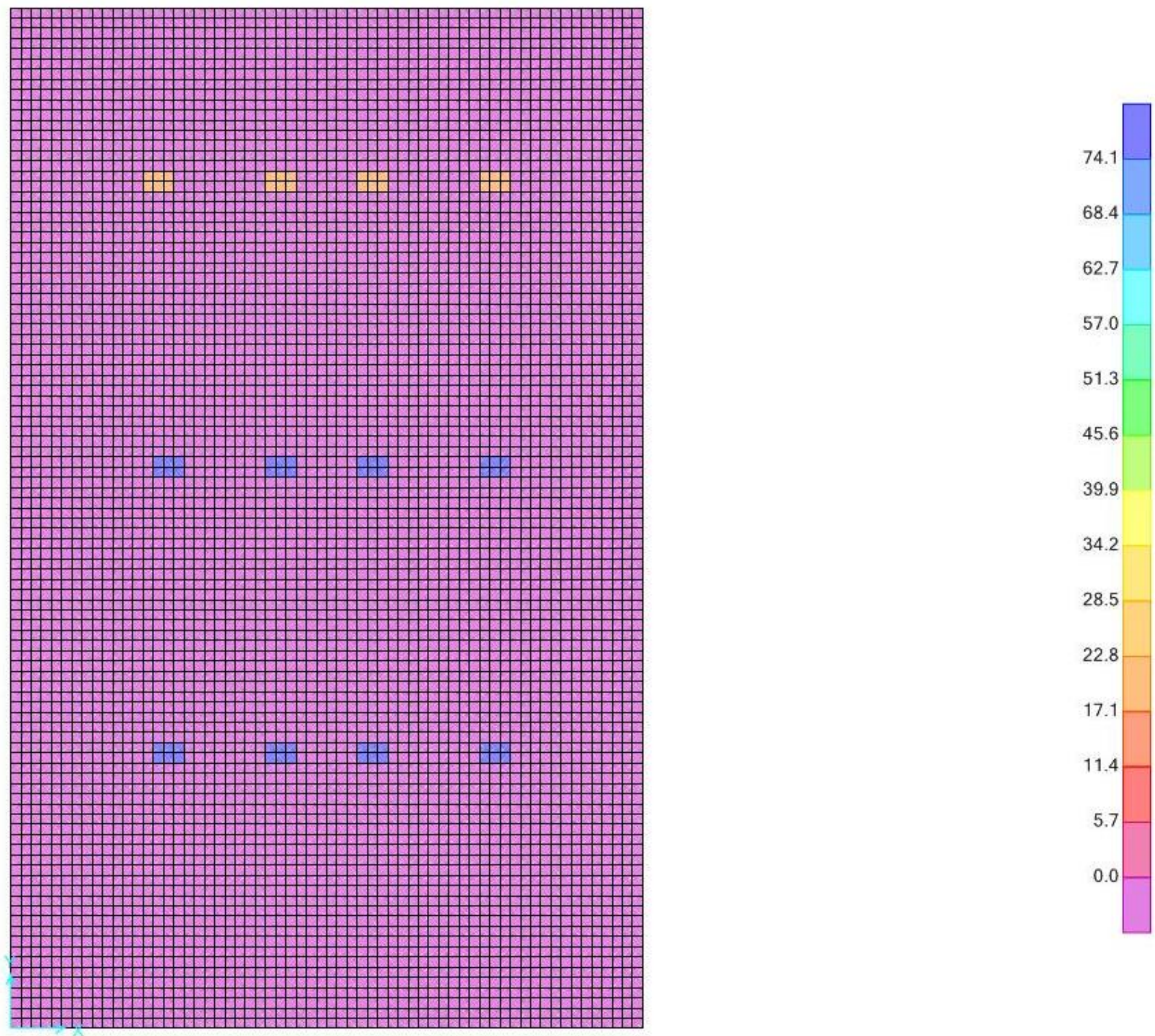


Figure 10: Loads from two HS20-44 trucks over the central girder (four 18.519 psi loads in yellow and eight 74.074 psi wheel loads in blue)

The goal of creating the model described over the past several paragraphs was to determine the minimum beam size necessary, in both steel and timber, to support the design load. In order for a beam to be sufficient, it had to meet three requirements. First, it had to have a depth greater than or equal to 1/30 the span length, as specified by the optional span-to-depth ratios in AASHTO Table 2.5.2.6.3-1. This requirement applied only to the steel beams. Second, it had to have a moment capacity capable of supporting the applied load. Third, it had to have a total deflection under the unfactored dead load alone of less than L/300. The first two requirements are specified or suggested by AASHTO. The third requirement was specific to this project, however. While AASHTO no longer specifies mandatory deflection limits for bridges, it does provide recommended values in the event that the owner or designer wishes to incorporate such restrictions. However, given that only the primary structural members were modeled in this project and the various transverse stiffeners were neglected, it was felt that the suggested deflection limit of L/800 was too strict. A more permissive value of L/300 was therefore adopted. The beam depth and deflection limits for each span length as adopted for this analysis are provided in Table 5.

Table 5: Beam Depth and Deflection Limits

Span (ft)	L/30 Beam Depth Limit (in.)	L/300 Deflection Limit (in.)
20	8	0.8
30	12	1.2
40	16	1.6
50	20	2
60	24	2.4
70	28	2.8
80	32	3.2
90	36	3.6
100	40	4

Based on the minimum beam depth required, as shown in Table 5, an initial trial section was selected for the model. This was taken from either the AISC Manual for steel sections or from the table *Section Properties of Structural Glued Laminated Timber* published by the AITC for wood beams. It is important to point out here that commercially available wide flange sections were used in the design of the bridges with a steel superstructure. These sections are optimized for use in buildings, where it is important to restrict the depth of members for architectural and practical reasons. In bridges, where such restrictions are not always necessary, more efficient and lighter weight members can be created through the design of plate girders. These tend to be deeper and narrower than commercial sections, resulting in a more efficient use of material. It was determined, however, that the design of plate girder sections was beyond the scope of a preliminary analysis such as this.

Another important point is that with both the steel and the wood superstructures, the same section was used for all three girders. This was based on Section 2.5.2.7.1 of the AASHTO LRFD specifications, which states that "[u]nless future widening is virtually inconceivable, the load carrying capacity of exterior beams shall not be less than the load carrying capacity of an interior beam" (AASHTO 2012). Because of this, only the most critical moment created in either the interior or the exterior girder was considered in design.

Once the model was run for the initial trial section, the dead load deflection could be immediately checked. If the value exceeded L/300, a new section was immediately tried. Once deflection was satisfied, the moment capacity of the section was checked. As previously stated, it was assumed that both the steel and timber beams, together with the concrete slab, exhibited fully composite behavior. The exact mechanisms used to achieve such behavior were not considered and are beyond the scope of this paper.

Composite action means that the steel or timber beam acts in concert with a portion of the deck slab to resist the applied moment. In essence, a section of the slab serves as an extended flange on the top of the beam, increasing the effective moment of inertia and the moment capacity of the section. The portion of the slab which acts in concert with the beam is referred to as the effective width. According to AASHTO Section 4.6.2.6, for the type of bridge design considered here, the effective width may be taken as the tributary area of the girder. That means that with girders spaced 12 feet on center and a deck overhang of 3.5 feet, the effective width for the exterior girders is 9.5 feet, while the interior girder has an effective width of 12 feet.

Based on that effective width, the trial section selected and the applied moment calculated by the SAP, it could be determined if the section was sufficient using the following sequence of equations, as adapted from *Steel Structures: Design and Behavior* by Charles G. Salmon and John E. Johnson:

$$A_{req} = \frac{M_u}{\emptyset_c F\left(\frac{d}{2} + t_s - \frac{a}{2}\right)} \qquad (eq. 1)$$

$$T = A_{req} F \qquad (eq. 2)$$

$$a = \frac{T}{.85f'_c b_E} \leq t_s \qquad (eq. 3)$$

$$\emptyset M_n = T\left(\frac{d}{2} + t_s - \frac{a}{2}\right) \geq M_u \qquad (eq. 4)$$

Where:

$A_{req} = area\ required\ to\ resist\ the\ moment\ (in.^2)$

$M_u = factored\ moment\ applied\ to\ trial\ section\ (kip - in.)$

$\emptyset_c = resistance\ factor\ for\ composite\ action, .85\ for\ steel$
$\qquad - concrete, assumed\ .75\ for\ wood - concrete$

$F = F_y = F'_b = allowable\ bending\ stress\ (ksi)$

$d = depth\ of\ trial\ section\ (in.)$

$t_s = thickness\ of\ concrete\ slab\ (in.)$

$a = depth\ of\ equivalent\ stress\ block\ (in.)$

$T = tensile\ force\ produced\ in\ girder\ (kips)$

$f'_c = compressive\ strength\ of\ concrete\ (ksi)$

$b_E = effective\ width\ of\ slab\ (in.)$

$M_n = fnominal\ moment\ capacity\ (kip - in.)$

In equation 1, there is a resistance factor $\emptyset_c$ which is applied to account for uncertainty in the degree of composite action between the two materials and which differs from the normal bending resistance factor. AASHTO does not provide any guidance on the choice of this factor. For that reason, the value of .85 for a steel and concrete composite used in the Salmon and Johnson book was adopted for the purposes of designing the steel sections. However, no published value was found for wood and concrete composites. For that reason, a judgement was made that a value of .75 would be appropriate for the initial analysis performed here given the uncertain nature of wood as a material. However, this value was not based on any tests or other forms of data. For that reason, it is strongly advised that this resistance factor be adjusted as deemed appropriate based on physical tests and statistical analyses thereof.

The procedure when using the above equations is to pick a trial section, input the depth of the section and an assumed value for "a" which is smaller than the thickness of the slab into equation 1, use the resulting area to calculate T, and then use T and the effective width of the slab to determine the actual value of "a." Provided that "a" is less than the slab thickness, the equations are valid and the nominal moment capacity of the section can be determined from equation 4. If this is greater than the applied moment, then the section chosen is satisfactory.

The formulas for calculating moment capacity depend on the maximum bending stress the material is capable of resisting. For steel that is a constant value, in this instance 50 ksi. However, that value varies for timber depending on a number of factors. This is shown below, as specified in Section 8.4.4 of AASHTO 2012 for glulam members.

$$F'_b = F_b C_{kf} C_m C_v C_d C_\lambda \qquad (eq. 5)$$

$$C_v = \left(\left(\frac{12}{d}\right)\left(\frac{5.125}{b}\right)\left(\frac{21}{L}\right)\right)^a \leq 1.0 \qquad (eq. 6)$$

Where:

$F'_b = adjusted\ bending\ stress\ (ksi)$

$F_b = reference\ bending\ stress = 2.6\ for\ 26F - 1.9E\ glulam\ (ksi)$

$C_{kf} = \frac{2.5}{\emptyset} = format\ conversion\ factor$

$\emptyset = .85\ for\ bending$

$C_m = wet\ service\ factor = \ .8\ for\ bending\ in\ wet\ conditions$

$C_v = volume\ factor$

$C_d = deck\ factor = 1.0\ except\ in\ special\ cases$

$C_\lambda = time\ effect\ factor = \ .8\ for\ Strength\ I\ limit\ state$

$d = member\ depth\ (in.)$

$b = member\ width\ (in.)$

$L = span\ length\ (ft)$

$a = .05\ for\ southern\ pine\ and\ .1\ otherwise$

Using the relationships specified above, it was possible to determine the beam sizes necessary to support the design loads for each span length. This, in turn, would permit an economic and environmental analysis to be performed.

3.2 Economic

The initial intent of this thesis was to perform an economic analysis comparing timber and steel. However, it was realized that the wide flange steel sections selected using the structural criteria were unlikely to be utilized in actual construction. It was therefore felt that any economic comparison based on these less efficient sections would be misleading. Additionally, without knowing site specific conditions, estimated costs for labor and other elements cannot be accurately predicted. As a result, no economic comparison was ultimately performed. However, the proposed methodology to do such an analysis has still been included.

Using the data obtained from the structural analysis regarding member sizes and quantities, initial construction costs for major components can be calculated based on the current five year averaged price list published by VTrans. The resulting figures only represent the value of the materials used for the superstructure construction. Specifically, they are based on the volume of concrete and pavement used for the deck, the length of railing utilized, the weight of rebar used for reinforcing, the weight of the structural steel sections and the volume of the glulam beams. The costs do not consider labor expenses, which would be a very significant component. However, it is expected that these would be similar for both the steel and timber bridge designs.

3.3 Environmental

As with the economic analysis, it was felt that the use of steel sections intended for use in buildings would lead to misleading results. Therefore, the proposed methodology has been included, but no data has been included. In order to assess the environmental impact of the hypothetical bridge designs, the embodied energy of the materials used would need to be calculated. The basic concept of embodied energy is that all of the energy used to gather, manufacture and transport a material throughout its life is assigned to the material itself, as though it actually contains it. The larger the embodied energy, the less environmentally friendly the material is. The values obtained through such an analysis obviously depend heavily on where the boundaries of the system contributing to the material are drawn. It is a common practice, and one which is suggested for this analysis, to examine the “cradle-to-gate” embodied energy. This includes all of the energy used to mine or harvest the material, everything used in its manufacture and processing and all of the transportation needed to reach its final destination. It does not incorporate anything that happens after it arrives at a job site, such as energy used in installation, building upkeep or end of life disposal. The largest omission resulting from the cradle-to-gate approach, at least in regards to bridges, is the energy related to end of life disposal. Steel can be easily recycled and reused for new products. At this time, however, there are few if any ways in which pressure treated timber can be salvaged. As a result, it is typically disposed of in landfills, resulting in significant economic and environmental costs.

For the designs described in this report, the material quantities estimated from the structural analysis would be used to determine the embodied energy associated with the structures. First, the material quantities obtained should be converted into kilograms. Then, utilizing the embodied energy coefficients from the *Inventory of Carbon and Energy Database*, the material weights can be used to calculate the amount of energy used to create and transport each component. This in turn would permit a direct environmental comparison between equivalently sized steel and timber bridges. For those wishing to perform their own comparisons, summary data from the *ICE* Database has been included in Appendix B and the list of references consulted by the authors of that report has been attached in Appendix C.

4. Results

Using the methodology outlined previously in section 3.1, the structural sections shown below in Table 3 were found to be satisfactory for the design load cases. In all cases, it was found that the moment created by the centrally placed loads was the critical force effect. It was also found that actual moment capacity never governed the section size chosen. Six of the nine steel girder sizes were chosen based on the minimum required beam depth. The remaining three were found based on the deflection criteria. It should once again be noted, however, that wide flange sections were used, rather than plate girders which could have been optimized to meet all three required criteria. A similar pattern was observed with the wood beams, where reductions in section size and weight were restricted by deflection limits long before the nominal moment capacity of the members was reached. It is expected that this trend would have been even more pronounced had the L/800 deflection limit been applied.

Based on the stated loads and selection criteria, the sections chosen for each of the nine span lengths have been included below. Table 6 shows the wide flange sections chosen for the girders along with the maximum moment and dead load deflection calculated in the SAP model. Table 7 provides the same information for wood beams, along with an additional column for the weight per foot. This is based on a density of 36 pcf, as indicated by the AITC southern pine glulam section properties table.

Table 6: Steel Girder Sections

Length (ft)	L/300 (in.)	Section	Moment (kip-in.)	DL Deflection (in.)
20	0.8	W8x13	223	0.24
30	1.2	W12x14	707	0.34
40	1.6	W16x31	2535	1.37
50	2	W21x57	5543	1.65
60	2.4	W24x76	8850	2.28
70	2.8	W30x108	11842	2.34
80	3.2	W33x130	18367	2.94
90	3.6	W36x170	24523	3.34
100	4	W40x211	31029	3.71

Table 7: Wood Girder Sections

Length (ft)	L/300 (in.)	Section (b x d, in.)	Weight (lbs/ft)	Moment (kip-in)	DL Deflection (in.)
20	0.8	3.5x8.25	7.2	68	0.24
30	1.2	3.5x12.375	10.8	327	0.37
40	1.6	5x22	27.5	1814	1.27
50	2	5x30.25	37.8	3670	1.69
60	2.4	6.75x33	55.7	5568	2.31
70	2.8	6.75x39.875	67.3	7291	2.76
80	3.2	8.5x44	93.5	11472	3.11
90	3.6	8.5x52.25	111.0	15242	3.27
100	4	10.5x55	144.4	19455	3.75

As noted previously, it was determined that performing a full economic and environmental analysis at this time would be inappropriate, given that steel sections optimized for use in buildings were used for the superstructure design. Cost estimates may be made on a unit basis using a variety of widely available but site specific data. They will thus not be discussed further. However, determining the environmental impact of either an individual material or an entire structure is a more difficult task. As discussed previously, it is suggested that a cradle-to-gate embodied energy analysis be performed. This requires the use of embodied energy coefficients. It was found that the *ICE Database* offered the most comprehensive and user friendly array of information on this topic. However, much of the source material for this database comes from Europe. Caution should thus be used when applying these values outside that region. Within this database are values for a number of different materials and conditions. After careful examination, it was determined that the following embodied energy coefficients would be most appropriate for the materials used in the bridge designs analyzed for this report. These values have been included in Table 8 below. The reader is encouraged, however, to make their own determination of appropriate values based on project specific criteria.

Table 8: Suggested Embodied Energy Coefficients

Material	Embodied Energy Coefficient (MJ/kg)	Notes
Steel Sections	21.50	EU recycled content
Glulam	12.00	Does not include energy if burnt
Concrete	.78	25-30 MPa strength
Rebar	17.40	EU recycled content
Asphalt Pavement	3.39	5% bitumen content

5. Conclusions

Based on SAP2000 models of 18 different bridges (nine span lengths modeled with two different girder materials), the size of steel and glulam sections required to support the AASHTO HL-93 live load were determined. It was found that glulam timber could be modeled in SAP with relative ease by defining it as an orthotropic material and determining the appropriate properties from sources such as the *Wood Handbook*. It was also determined that standard glulam section sizes can provide sufficient strength and moment capacity to meet the design requirements for short and medium span vehicular bridges.

Unfortunately, given the steel sections used during the structural modeling, it was deemed unrealistic to perform a full economic and environmental analysis at this time. As a result, the original question regarding the relative benefits of steel and timber superstructures could not be fully answered. However, a general methodology for answering these questions was proposed. Of particular importance is the selection of embodied energy coefficients. Several suggested values have been proposed, but future research should be conducted to determine more precise values.

In general, there is still significant need for future research. The results of this thesis do not provide any information to suggest that glulams should not be used for vehicular bridges. However, the relative environmental impacts and economic feasibility of steel and glulam bridges has not yet been determined. Further study is therefore required to assess these questions. It is suggested that future research focus on specific sites in order to compare bridges under real world conditions. Efforts should also be made to develop regional embodied energy coefficients and to develop standardized procedures for comparing the environmental impacts of different alternatives.

6. References

Alcorn, J. A. and G. Baird (1996). "Use of a hybrid energy analysis method for evaluating the embodied energy of building materials." *Renewable Energy*, 8(1-4).

American Association of State Highway and Transportation Officials (2012). *AASHTO LRFD Bridge Design Specifications.* Washington, D.C.: AASHTO.

American Institute of Steel Construction (2013). *Steel Construction Manual.* 14th Edition. Chicago: AISC.

Associated Press. (2013). "Report: Over 65,000 U.S. bridges in need of repair." USA Today. <http://www.usatoday.com/story/news/nation/2013/09/15/bridges-need-repair/2816881/> (February 3, 2015).

AITC. (2007). "Glulam: Engineered Strength. Unsurpassed Versatility. Dependable Quality." American Institute of Timber Construction. <http://www.aitc-glulam.org/glulam.asp> (April 12, 2015).

AITC. (2007). "Section Properties of Structural Glued Laminated Timber." American Institute of Timber Construction. < http://www.aitcglulam.org/pdf/Section/sp_section_properties.pdf> (March 10, 2015).

ASCE. (2013). "2013 Report Card for America's Infrastructure." American Society of Civil Engineers. <http://www.infrastructurereportcard.org/bridges/> (February 3, 2015).

Buchanan, Andrew H. and Brian G. Honey (2003). "Energy and carbon dioxide implications of building construction." *Energy and Buildings*, 20(3): *ScienceDirect*: Web. <http://www.sciencedirect.com/science/article/pii/0378778894900248> (Aug. 30, 2014).

Griffin, C.T., Reed, B., & Hsu, S. (2010). "Comparing the embodied energy of structural systems in buildings." In: Cruz P., editor. *Structures and Architecture: Proceedings of the 1st International Conference on Structures & Architecture (ICSA2010)*. Guimaraes, Portugal, July 21-23, 2010.

Hammond, Geoff and Craig Jones (2011). "Embodied energy and embodied carbon footprint – The ICE database." [Excel download] *Circular Ecology,* <http://www.circularecology.com/embodied-energy-and-carbon-footprint-database.html#.VA5LEcfD_IU> (Sept. 8, 2014).

Harris, D.J. (1999). "A quantitative approach to the assessment of the environmental impact of building materials." *Building and Environment*, 34(6): *ScienceDirect.* Web. <http://www.sciencedirect.com/science/article/pii/S0360132398000584> (Aug. 30, 2014).

Houska, C. (2007) "Deicing Salt – Recognizing the Corrosion Threat." TMR Consulting. Pittsburgh, Pennsylvania.

Kirby, R.S., Withington, S., et al. (1990). *Engineering in History*. Dover, New York.

Morel, J. C., A. Mesbah, M. Oggero, P. Walker (2010). “Building houses with local materials: means to drastically reduce the environmental impact of construction.” *Building and Environment*, 36(10): *ScienceDirect*. Web. <http://www.sciencedirect.com/science/article/pii/S0360132300000548>. (Nov. 26, 2013).

Reddy, Venkatarama B. V. and K.S. Jagadish (2003). “Embodied energy of common and alternative building materials and technologies.” *Energy and Buildings*, 35(2): *ScienceDirect*: Web. < http://www.sciencedirect.com/science/article/pii/S0378778801001414> (Aug. 30, 2014).

Salmon, C. G., and Johnson, J. E. (1996). *Steel Structures: Design and Behavior.* 4th ed. Upper Saddle River, New Jersey: Prentice-Hall.

United States Department of Agriculture. United States Forest Service. Forest Products Laboratory (2010). *Wood Handbook: Wood as an Engineering Material.* Washington, D.C.: Government Printing Office.

United States Department of Agriculture. United States Forest Service. Michael A. Ritter (1990). *Timber Bridges: Design, Construction, Inspection, and Maintenance*. Washington, D.C.: Government Printing Office. *Hathi Trust Digital Library*. Web. <http://babel.hathitrust.org/cgi/pt?id=umn.31951d00276578k;view=1up;seq=7> (Aug. 31, 2014).

United States Department of Transportation. Federal Highway Administration. William J. Wright (2012). *Steel Bridge Design Handbook.* Washington, D.C.: Government Printing Office.

```
function [ Max, Position ] = SSBmoving3point( L,p1,p2,p3,a12,a23,deltax )
% This function calculates the maximum moment produced by a series of up to
% three point loads moving across the length of a simply supported beam. It
% also returns the position of the first load (relative to the left end of
% the beam) at the time the maximum moment is produced. The position of the
% other two loads can be calculated based on the distance between the loads.
% If there are only two point loads applied, enter 0 for the value of "p3".
% Also, decreasing the value of "deltax" increases the accuracy but results
% in a slower calculation.
%
% CALL
% For a simply supported beam spanning distance "L", up to three point
% loads with magnitudes "p1", "p2" and "p3", distance between the first and
% second point load "a12", distance between the second and third point
% loads "a23" and iteration distance "deltax":
% [ Max, Position ] = SSBmoving3point( L,p1,p2,p3,a12,a23,deltax )

x = 0:deltax:L;
d1 = 0:deltax:L+a12+a23;
d2 = d1-a12;
d3 = d1-a12-a23;

P1=zeros(1,length(d1));
P2=zeros(1,length(d1));
P3=zeros(1,length(d1));
By=zeros(1,length(d1));
Ay=zeros(1,length(d1));
m=zeros(1,length(x));

for n=1:length(d1)
    if d1(n)>L
        P1(n)=0;
    else
        P1(n)=p1;
    end

    if d2(n)<0 || d2(n)>L
        P2(n)=0;
    else
        P2(n)=p2;
    end

    if d3(n)<0 || d3(n)>L
        P3(n)=0;
    else
        P3(n)=p3;
    end

    % Reactions
    By(n) = (P3(n).*d3(n)+P2(n).*d2(n)+P1(n).*d1(n))./L; % Reaction at right end of beam
    Ay(n) = P3(n)+P2(n)+P1(n)-By(n); % Reaction at left end of beam

    for k=1:length(x)
        if x(k)<d3(n)
```

```
            m(k)=Ay(n).*x(k);
        elseif x(k)>=d3(n) & x(k)<d2(n)
            m(k)=Ay(n).*x(k)-P3(n).*(x(k)-d3(n));
        elseif x(k)>=d2(n) & x(k)<d1(n)
            m(k)=Ay(n).*x(k)-P3(n).*(x(k)-d3(n))-P2(n).*(x(k)-d2(n));
        else
            m(k)=Ay(n).*x(k)-P3(n).*(x(k)-d3(n))-P2(n).*(x(k)-d2(n))-P1(n).*(x(k)-d1(n));
        end
    end
    M{n}=m;
end

for k=1:length(d1)
    a(k)=max(M{k}); % Finds the maximum moment from each load position
end

Max=max(a); % Finds the overall maximum moment from all tested cases
c=find(a==Max,1); % Identifies which combination produced the maximum moment
Position=d1(c); % Provides the position of the first load (P1) measured from the left end↙
of the beam for the location which produced the maximum moment


end
```

```
% This script calculates the maximum moment produced by three point loads
% which are allowed to move across a simply supported beam. The distance
% between the first and second point loads is a fixed user defined value,
% but the distance between the second and third point load may be allowed
% to vary between a maximum and minimum set value. The code returns the
% value of the maximum moment produced, the position of the first load
% relative to the left end of the beam for the load position which produces
% the maximum moment and the value of the distance between the second and
% third loads which resulted in the largest moment.
%
% This code was designed to model the behavior of the HS20-44 truck used in
% the AASHTO HL-93 design load for bridges. It may also be used to model the
% design tandem by setting p1=p2=25, p3=0, a12=4 and a23min=a23max=0. Units
% are assumed to be kips and feet, consistent with the AASHTO
% Specifications, but the code is actually unit agnostic.

clear all
clc

L = 100; % Span length
p1 = 8; % Value of the first point load
p2 = 32; % Value of the second point load
p3 = 32; % Value of the third point load
a12 =14; % Distance between the first and second point load
a23min = 14; % Minimum distance between second and third point load
a23max = 30; % Maximum distance between the second and third point load
deltax = L/1200; % Change in position of the loads between each calculation

x=0:deltax:L;
a23=a23min:deltax:a23max;

M=zeros(1,length(a23));
P=zeros(1,length(a23));

for k=1:length(a23)
    [M(k), P(k)]=SSBmoving3point(L,p1,p2,p3,a12,a23(k),deltax);
end

Maximum=max(M);
c=find(M==Maximum);
Position=P(c);
Length=a12+a23(c);

fprintf('Maximum moment produced = %f \n',Maximum)
fprintf('Position of front axle when the maximum moment is produced = %f \n',Position)
fprintf('Total length of truck which produced the maximum moment = %f \n\n',Length)
```

INVENTORY OF CARBON & ENERGY (ICE) SUMMARY

Materials	Embodied Energy & Carbon Coefficients			Comments
	EE - MJ/kg	EC - kgCO2/kg	EC - kgCO2e/kg	EE = Embodied Energy, EC = Embodied Carbon
Aggregate				
General (Gravel or Crushed Rock)	0.083	0.0048	0.0052	Estimated from measured UK industrial fuel consumption data
Aluminium	Main data source: International Aluminium Institute (IAI) LCA studies (www.world-aluminium.org)			
General	155	8.24	9.16	Assumed (UK) ratio of 25.6% extrusions, 55.7% Rolled & 18.7% castings. Worldwide average recycled content of 33%.
Virgin	218	11.46	12.79	
Recycled	29.0	1.69	1.81	
Cast Products	159	8.28	9.22	Worldwide average recycled content of 33%.
Virgin	226	11.70	13.10	
Recycled	25.0	1.35	1.45	
Extruded	154	8.16	9.08	Worldwide average recycled content of 33%.
Virgin	214	11.20	12.50	
Recycled	34.0	1.98	2.12	
Rolled	155	8.26	9.18	Worldwide average recycled content of 33%.
Virgin	217	11.50	12.80	
Recycled	28	1.67	1.79	
Asphalt				
Asphalt, 4% (bitumen) binder content (by mass)	2.86	0.059	0.066	1.68 MJ/kg Feedstock Energy (Included). Modelled from the bitumen binder content. The fuel consumption of asphalt mixing operations was taken from the Mineral Products Association (MPA). It represents typical UK industrial data. Feedstock energy is from the bitumen content.
Asphalt, 5% binder content	3.39	0.064	0.071	2.10 MJ/kg Feedstock Energy (Included). Comments from 4% mix also apply.
Asphalt, 6% binder content	3.93	0.068	0.076	2.52 MJ/kg Feedstock Energy (Included). Comments from 4% mix also apply.
Asphalt, 7% binder content	4.46	0.072	0.081	2.94 MJ/kg Feedstock Energy (Included). Comments from 4% mix also apply.
Asphalt, 8% binder content	5.00	0.076	0.086	3.36 MJ/kg Feedstock Energy (Included). Comments from 4% mix also apply.
Bitumen				
General	51	0.38 - 0.43 (?)	0.43 - 0.55 (?)	42 MJ/kg Feedstock Energy (Included). Feedstock assumed to be typical energy content of Bitumen. Carbon dioxide emissions are particularly difficult to estimate, range given.
Brass				
General	44.00	2.46 (?)	2.64 (?)	Poor data availability. It is believed that the data may be largely dependent upon ore grade. Poor carbon data, making estimate of embodied carbon difficult.
Virgin	80.00	4.47 (?)	4.80 (?)	
Recycled	20.00	1.12 (?)	1.20 (?)	
Bricks				
General (Common Brick)	3.00	0.23	0.24	
EXAMPLE: Single Brick	6.9 MJ per brick	0.53 kgCO2 per brick	0.55	Assuming 2.3 kg per brick.
Limestone	0.85	?	-	
Bronze				
General	69.0 (?)	3.73 (?)	4.0 (?)	Average of the only two references
Carpet				
General Carpet	74 (187 per sqm)	3.9 (9.8 per sqm)	-	For per square meter estimates see material profile. Difficult to estimate, taken from Ref. 94.
Felt (Hair and Jute) Underlay	19.00	0.97	-	Ref. 94.
Nylon (Polyamide), pile weight 300 g/m2	130 MJ per sqm	6.7 (GWP) per sqm	6.7 (GWP) per sqm	Total weight of this carpet 1,477 g/m2. See Refs. 277 & 279. These carpets (inc. below) are a tufted surface pile made of 100% nylon (polyamide) with a woven textile backing and flame proofed on the basis of aluminium hydroxide.
Nylon (Polyamide), pile weight 500 g/m2	180 MJ per sqm	9.7 (GWP) per sqm	9.7 (GWP) per sqm	Total weight of this carpet 1,837 g/m2. See Refs. 277 & 279.
Nylon (Polyamide), pile weight 700 g/m2	230 MJ per sqm	12.7 (GWP) per sqm	12.7 (GWP) per sqm	Total weight of this carpet 2,147 g/m2. See Refs. 277 & 279.
Nylon (Polyamide), pile weight 900 g/m2	277 MJ per sqm	15.6 (GWP) per sqm	15.6 (GWP) per sqm	Total weight of this carpet 2,427 g/m2. See Refs. 277 & 279.
Nylon (Polyamide), pile weight 1100 g/m2	327 MJ per sqm	18.4 (GWP) per sqm	18.4 (GWP) per sqm	Total weight of this carpet 2,677 g/m2. See Refs. 277 & 279.
Carpet tiles, nylon (Polyamide), pile weight 300 g/m2	178 MJ per sqm	7.75 (GWP) per sqm	7.75 (GWP) per sqm	Total weight of this carpet 4,123 g/m2. See Refs. 277 & 279. These carpet tiles (inc. below) are a tufted surface pile made of 100% nylon (polyamide) fleece-covered bitumen backing and flame-proofed on the basis of aluminium hydroxide
Carpet tiles, nylon (Polyamide), pile weight 500 g/m2	229 MJ per sqm	10.7 (GWP) per sqm	10.7 (GWP) per sqm	Total weight of this carpet 4,373 g/m2. See Refs. 277 & 279.
Carpet tiles, nylon (Polyamide), pile weight 700 g/m2	279 MJ per sqm	13.7 (GWP) per sqm	13.7 (GWP) per sqm	Total weight of this carpet 4,623 g/m2. See Refs. 277 & 279.
Carpet tiles, nylon (Polyamide), pile weight 900 g/m2	328 MJ per sqm	16.7 (GWP) per sqm	16.7 (GWP) per sqm	Total weight of this carpet 4,873 g/m2. See Refs. 277 & 279.
Carpet tiles, nylon (Polyamide), pile weight 1100 g/m2	378 MJ per sqm	19.7 (GWP) per sqm	19.7 (GWP) per sqm	Total weight of this carpet 5,123 g/m2. See Refs. 277 & 279.
Polyethylterepthalate (PET)	106.50	5.56	-	Includes feedstock energy
Polypropylene	95.40	4.98	-	Includes feedstock energy, for per square meter see material profile
Polyurethane	72.10	3.76	-	Includes feedstock energy
Rubber	67.5 to 140	3.61 to 7.48	-	
Saturated Felt Underlay (impregnated with Asphalt or tar)	31.70	1.65	-	Ref. 94.
Wool	106.00	5.53	-	For per square meter see material profile. See Refs. 63, 201, 202 & 281 (Same author).
Cement				

INVENTORY OF CARBON & ENERGY (ICE) SUMMARY

Materials	Embodied Energy & Carbon Coefficients			Comments
	EE - MJ/kg	EC - kgCO2/kg	EC - kgCO2e/kg	EE = Embodied Energy, EC = Embodied Carbon
General (UK weighted average)	4.5	0.73	0.74	Weighted average of all cement consumed within the UK. This includes all factory made cements (CEM I, CEM II, CEM III, CEM IV) and further blending of fly ash and ground granulated blast furnace slag. This data has been estimated from the British Cement Association's factsheets (see Ref. 59). 23% cementitious additions on average.
Average CEM I Portland Cement, 94% Clinker	5.50	0.93	0.95	This is a standard cement with no cementitious additions (i.e. fly ash or blast furnace slag). Composition 94% clinker, 5% gypsum, 1% minor additional constituents (mac's). This data has been estimated from the British Cement Association's factsheets (see Ref. 59.).
6-20% Fly Ash (CEM II/A-V)	5.28 to 4.51	0.88 (@ 6%) to 0.75 (@ 20%)	0.89 to 0.76	See material profile for further details.
21-35% Fly Ash (CEM II/B-V)	4.45 to 3.68	0.74 to 0.61	0.75 to 0.62	
21-35% GGBS (CEM II/B-S)	4.77 to 4.21	0.76 to 0.64	0.77 to 0.65	
36-65% GGBS (CEM III/A)	4.17 to 3.0	0.63 to 0.38	0.64 to 0.39	
66-80% GGBS (CEM II/B)	2.96 to 2.4	0.37 to 0.25	0.38 to 0.26	
Fibre Cement Panels - Uncoated	10.40	1.09	-	Few data points. Selected data modified from Ref. 107.
Fibre Cement Panels - (Colour) Coated	15.30	1.28	-	
Mortar (1:3 cement:sand mix)	1.33	0.208	0.221	Values estimated from the ICE Cement, Mortar & Concrete Model
Mortar (1:4)	1.11	0.171	0.182	
Mortar (1:5)	0.97	0.146	0.156	
Mortar (1:6)	0.85	0.127	0.136	
Mortar (1:½:4½ Cement:Lime:Sand mix)	1.34	0.200	0.213	
Mortar (1:1:6 Cement:Lime:Sand mix)	1.11	0.163	0.174	
Mortar (1:2:9 Cement:Lime:Sand mix)	1.03	0.145	0.155	
Cement stabilised soil @ 5%	0.68	0.060	0.061	Assumed 5% cement content.
Cement stabilised soil @ 8%	0.83	0.082	0.084	Assumed 8% stabiliser contents (6% cement and 2% quicklime)

INVENTORY OF CARBON & ENERGY (ICE) SUMMARY

Materials	Embodied Energy & Carbon Coefficients									Comments
	EE - MJ/kg			EC - kgCO2/kg			EC - kgCO2e/kg			EE = Embodied Energy, EC = Embodied Carbon
Ceramics										
General	10.00			0.66			0.70			Very large data range, difficult to select values for general ceramics.
Fittings	20.00			1.07			1.14			Ref. 1.
Sanitary Products	29.00			1.51			1.61			Limited data.
Tiles and Cladding Panels	12.00			0.74			0.78			Difficult to select, large range, limited data. See Ref. 292.
Clay										
General (Simple Baked Products)	3.00			0.23			0.24			General simple baked clay products (inc. terracotta and bricks)
Tile	6.50			0.45			0.48			
Vitrified clay pipe DN 100 & DN 150	6.20			0.44			0.46			
Vitrified clay pipe DN 200 & DN 300	7.00			0.48			0.50			
Vitrified clay pipe DN 500	7.90			0.52			0.55			
Concrete										
General	0.75			0.100			0.107			**It is strongly recommended to avoid selecting a 'general' value for concrete.** Selecting data for a specific concrete type (often a ready mix concrete) will give greater accuracy, please see material profile. Assumed cement content 12% by mass.
16/20 Mpa	0.70			0.093			0.100			Using UK weighted average cement (more representative of 'typical' concrete mixtures).
20/25 MPa	0.74			0.100			0.107			
25/30 MPa	0.78			0.106			0.113			
28/35 MPa	0.82			0.112			0.120			
32/40 MPa	0.88			0.123			0.132			
40/50 MPa	1.00			0.141			0.151			
% Cement Replacement - Fly Ash	**0%**	**15%**	**30%**	**0%**	**15%**	**30%**	**0%**	**15%**	**30%**	**Note 0% is a concrete using a CEM I cement (not typical)**
GEN 0 (6/8 MPa)	**0.55**	0.52	0.47	**0.071**	0.065	0.057	**0.076**	0.069	0.061	**Compressive strength designation C6/8 Mpa. 28 day compressive strength under British cube method of 8 MPa, under European cylinder method 6 MPa.** Possible uses: Kerb bedding and backing. Data is only cradle to factory gate but beyond this the average delivery distance of ready mix concrete is 8.3 km by road (see Ref. 244).
GEN 1 (8/10 MPa)	**0.70**	0.65	0.59	**0.097**	0.088	0.077	**0.104**	0.094	0.082	Possible uses: mass concrete, mass fill, mass foundations, trench foundations, blinding, strip footing.
GEN 2 (12/15 MPa)	**0.76**	0.71	0.64	**0.106**	0.098	0.087	**0.114**	0.105	0.093	-
GEN 3 (16/20 MPa)	**0.81**	0.75	0.68	**0.115**	0.105	0.093	**0.123**	0.112	0.100	Possible uses: garage floors.
RC 20/25 (20/25 MPa)	**0.86**	0.81	0.73	**0.124**	0.114	0.101	**0.132**	0.122	0.108	-
RC 25/30 (25/30 MPa)	**0.91**	0.85	0.77	**0.131**	0.121	0.107	**0.140**	0.130	0.115	Possible uses: reinforced foundations.
RC 28/35 (28/35 MPa)	**0.95**	0.90	0.82	**0.139**	0.129	0.116	**0.148**	0.138	0.124	Possible uses: reinforced foundations, ground floors.
RC 32/40 (32/40 MPa)	**1.03**	0.97	0.89	**0.153**	0.143	0.128	**0.163**	0.152	0.136	Possible uses: structural purposes, in situ floors, walls, superstructure.
RC 40/50 (40/50 MPa)	**1.17**	1.10	0.99	**0.176**	0.164	0.146	**0.188**	0.174	0.155	Possible uses: high strength applications, precasting.
PAV1	**0.95**	0.89	0.81	**0.139**	0.129	0.115	**0.148**	0.138	0.123	Possible uses: domestic parking and outdoor paving.
PAV2	**1.03**	0.97	0.89	**0.153**	0.143	0.128	**0.163**	0.152	0.137	Possible uses: heavy duty outdoor paving.
% Cement Replacement - Blast Furnace Slag	**0%**	**25%**	**50%**	**0%**	**25%**	**50%**	**0%**	**15%**	**30%**	**Note 0% is a concrete using a CEM I cement**
GEN 0 (6/8 MPa)	**0.55**	0.48	0.41	**0.071**	0.056	0.042	**0.076**	0.060	0.045	See fly ash mixtures
GEN 1 (8/10 MPa)	**0.70**	0.60	0.50	**0.097**	0.075	0.054	**0.104**	0.080	0.058	
GEN 2 (12/15 MPa)	**0.76**	0.62	0.55	**0.106**	0.082	0.061	**0.114**	0.088	0.065	
GEN 3 (16/20 MPa)	**0.81**	0.69	0.57	**0.115**	0.090	0.065	**0.123**	0.096	0.070	
RC 20/25 (20/25 MPa)	**0.86**	0.74	0.62	**0.124**	0.097	0.072	**0.132**	0.104	0.077	
RC 25/30 (25/30 MPa)	**0.91**	0.78	0.65	**0.131**	0.104	0.076	**0.140**	0.111	0.081	
RC 28/35 (28/35 MPa)	**0.95**	0.83	0.69	**0.139**	0.111	0.082	**0.148**	0.119	0.088	
RC 32/40 (32/40 MPa)	**1.03**	0.91	0.78	**0.153**	0.125	0.094	**0.163**	0.133	0.100	
RC 40/50 (40/50 MPa)	**1.17**	1.03	0.87	**0.176**	0.144	0.108	**0.188**	0.153	0.115	
PAV1	**0.95**	0.82	0.70	**0.139**	0.111	0.083	**0.148**	0.118	0.088	
PAV2	**1.03**	0.91	0.77	**0.153**	0.125	0.094	**0.163**	0.133	0.100	

COMMENTS

The first column represents standard concrete, created with a CEM I Portland cement. The other columns are estimates based on a direct substitution of fly ash or blast furnace slag in place of the cement content. The ICE Cement, Mortar & Concrete Model was applied. **Please see important notes in the concrete material profile.**

	EE - MJ/kg	EC - kgCO2/kg	EC - kgCO2e/kg	Comments
REINFORCED CONCRETE - Modification Factors				
For reinforcement add this value to the appropriate concrete coefficient for each 100 kg of rebar per m3 of concrete	1.04	0.072	0.077	Add for each 100 kg steel rebar per m3 concrete. Use multiple of this value, i.e. for 150 kg steel use a factor of 1.5 times these values.
EXAMPLE: Reinforced RC 25/30 MPa (with 110 kg per m3 concrete)	1.92 MJ/kg (0.78 + 1.04 * 1.1)	0.185 kgCO2/kg (0.106 + 0.072 * 1.1)	0.198 kgCO2/kg (0.113 + 0.077 * 1.1)	with 110 kg rebar per m3 concrete. UK weighted average cement. This assumes the UK typical steel scenario (59% recycled content). Please consider if this is in line with the rest of your study (goal and scope) or the requirements of a predefined method.
PRECAST (PREFABRICATED) CONCRETE - Modification Factors				
For precast add this value to the selected coefficient of the appropriate concrete mix	0.45	0.027	0.029	For each 1 kg precast concrete. This example is using a RC 40/50 strength class and is not necessarily indicative of an average precast product. Includes UK recorded plant operations and estimated transportation of the constituents to the factory gate (38km aggregates, estimated 100km cement). Data is only cradle to factory gate but beyond this the average delivery distance of precast is 155km by road (see Ref. 244). UK weighted average cement. See also the new report on precast concrete pipes (Ref 300).
EXAMPLE: Precast RC 40/50 MPa	1.50 MJ/kg (1.00 + 0.50)	0.168 kgCO2/kg (0.141 + 0.027)	0.180 kgCO2/kg (0.151 + 0.029)	
EXAMPLE: Precast RC 40/50 with reinforcement (with 80kg per m^3)	2.33 MJ/kg (1.50 + 1.04 * 0.8)	0.229 kgCO2/kg (0.171 + 0.072 * 0.8)	0.242 kgCO2/kg (0.180 + 0.077 * 0.8)	
CONCRETE BLOCKS (ICE CMC Model Values)				
Block - 8 MPa Compressive Strength	0.59	0.059	0.063	Estimated from the concrete block mix proportions, plus an allowance for concrete block curing, plant operations and transport of materials to factory gate.
Block - 10 MPa	0.67	0.073	0.078	
Block -12 MPa	0.72	0.082	0.088	
Block -13 MPa	0.83	0.100	0.107	

INVENTORY OF CARBON & ENERGY (ICE) SUMMARY

Materials	Embodied Energy & Carbon Coefficients			Comments
	EE - MJ/kg	EC - kgCO2/kg	EC - kgCO2e/kg	EE = Embodied Energy, EC = Embodied Carbon
Autoclaved Aerated Blocks (AAC's)	**3.50**	**0.24 to 0.375**	**-**	Not ICE CMC model results.
NOMINAL PROPORTIONS METHOD (Volume), Proportions from BS 8500:2006 (ICE Cement, Mortar & Concrete Model Calculations)				
1:1:2 Cement:Sand:Aggregate	**1.28**	**0.194**	**0.206**	High strength concrete. All of these values were estimated assuming the **UK average content of cementitious additions** (i.e. fly ash, GGBS) for **factory supplied cements** in the UK, see Ref. 59, plus the proportions of other constituents.
1:1.5:3	**0.99**	**0.145**	**0.155**	Often used in floor slab, columns & load bearing structure.
1:2:4	**0.82**	**0.116**	**0.124**	Often used in construction of buildings under 3 storeys.
1:2.5:5	**0.71**	**0.097**	**0.104**	
1:3:6	**0.63**	**0.084**	**0.090**	Non-structural mass concrete.
1:4:8	**0.54**	**0.069**	**0.074**	
BY CEM I CEMENT CONTENT - kg CEM I cement content per cubic meter concrete (ICE CMC Model Results)				
120 kg / m^3 concrete	**0.49**	**0.060**	**0.064**	Assumed density of 2,350 kg/m3. Interpolation of the CEM I cement content is possible. These numbers assume the **CEM I cement content (not the total cementitious content**, i.e. they do not include cementitious additions). They may also be used for fly ash mixtures without modification, but they are likely to slightly underestimate mixtures that have additional GGBS due to the higher embodied energy and carbon of GGBS (in comparison to aggregates and fly ash).
200 kg / m^3 concrete	**0.67**	**0.091**	**0.097**	
300 kg / m^3 concrete	**0.91**	**0.131**	**0.140**	
400kg / m^3 concrete	**1.14**	**0.170**	**0.181**	
500 kg / m^3 concrete	**1.37**	**0.211**	**0.224**	
MISCELLANEOUS VALUES				
Fibre-Reinforced	**7.75 (?)**	**0.45 (?)**	**-**	Literature estimate, likely to vary widely. High uncertainty.
Very High GGBS Mix	**0.66**	**0.049**	**0.050**	Data based on Lafarge 'Envirocrete', which is a C28/35 MPa, very high GGBS replacement value concrete

INVENTORY OF CARBON & ENERGY (ICE) SUMMARY

Materials	Embodied Energy & Carbon Coefficients			Comments
	EE - MJ/kg	EC - kgCO2/kg	EC - kgCO2e/kg	EE = Embodied Energy, EC = Embodied Carbon
Copper				
EU Tube & Sheet	**42.00**	**2.60**	**2.71**	EU production data, estimated from Kupfer Institut LCI data. 37% recycled content (the 3 year world average). World average data is expected to be higher than these values.
Virgin	57.00	3.65	3.81	
Recycled	16.50	0.80	0.84	
Recycled from high grade scrap	**18 (?)**	**1.1 (?)**		Uncertain, difficult to estimate with the data available.
Recycled from low grade scrap	**50 (?)**	**3.1 (?)**		
Glass				
Primary Glass	**15.00**	**0.86**	**0.91**	Includes process CO2 emissions from primary glass manufacture.
Secondary Glass	**11.50**	**0.55**	**0.59**	EE estimated from Ref 115.
Fibreglass (Glasswool)	**28.00**	**1.54**	**-**	Large data range, but the selected value is inside a small band of frequently quoted values.
Toughened	**23.50**	**1.27**	**1.35**	Only three data sources
Insulation				
General Insulation	**45.00**	**1.86**	**-**	Estimated from typical market shares. Feedstock Energy 16.5 MJ/kg (Included)
Cellular Glass	**27.00**	**-**	**-**	Ref. 54.
Cellulose	**0.94 to 3.3**	**-**	**-**	
Cork	**4.00**	**0.19**	**-**	Ref. 55.
Fibreglass (Glasswool)	**28.00**	**1.35**	**-**	Poor data difficult to select appropriate value
Flax (Insulation)	**39.50**	**1.70**	**-**	Ref. 2. 5.97 MJ/kg Feedstock Energy (Included)
Mineral wool	**16.60**	**1.20**	**1.28**	
Paper wool	**20.17**	**0.63**	**-**	Ref. 2
Polystyrene	**See Plastics**	**See Plastics**	**-**	see plastics
Polyurethane	**See Plastics**	**See Plastics**	**-**	see plastics
Rockwool	**16.80**	**1.05**	**1.12**	Cradle to Grave
Woodwool (loose)	**10.80**	**-**	**-**	Ref. 205.
Woodwool (Board)	**20.00**	**0.98**	**-**	Ref. 55.
Wool (Recycled)	**20.90**	**-**	**-**	Refs. 63, 201, 202 & 281.
Iron				
General	**25.00**	**1.91 (?)**	**2.03**	It was difficult to estimate the embodied energy and carbon of iron with the data available.
Lead				
General	**25.21**	**1.57**	**1.67**	Allocated (divided) on a mass basis, assumes recycling rate of 61%
Virgin	49.00	3.18	3.37	
Recycled	10.00	0.54	0.58	Scrap batteries are a main feedstock for recycled lead
Lime				
General	**5.30**	**0.76**	**0.78**	Embodied carbon was difficult to estimate
Linoleum				
General	**25.00**	**1.21**	**-**	Data difficult to select, large data range.
Miscellaneous				
Asbestos	**7.40**	**-**	**-**	Ref. 4.
Calcium Silicate Sheet	**2.00**	**0.13**	**-**	Ref. 55.
Chromium	**83**	**5.39**	**-**	Ref. 22.
Cotton, Padding	**27.10**	**1.28**	**-**	Ref. 38.
Cotton, Fabric	**143**	**6.78**	**-**	Ref. 38.
Damp Proof Course/Membrane	**134 (?)**	**4.2 (?)**	**-**	Uncertain estimate.
Felt General	**36**	**-**	**-**	
Flax	**33.50**	**1.70**	**-**	Ref. 2.
Fly Ash	**0.10**	**0.008**	**-**	No allocation from fly ash producing system.
Grit	**0.12**	**0.01**	**-**	Ref. 114.
Ground Limestone	**0.62**	**0.032**	**-**	
Carpet Grout	**30.80**	**-**	**-**	Ref. 169.
Glass Reinforced Plastic - GRP - Fibreglass	**100**	**8.10**	**-**	Ref. 1.
Lithium	**853**	**5.30**	**-**	Ref. 22.
Mandolite	**63**	**1.40**	**-**	Ref. 1.
Mineral Fibre Tile (Roofing)	**37**	**2.70**	**-**	Ref. 1.
Manganese	**52**	**3.50**	**-**	Ref. 22.
Mercury	**87**	**4.94**	**-**	Ref. 22.
Molybedenum	**378**	**30.30**	**-**	Ref. 22.
Nickel	**164**	**12.40**	**-**	Ref. 114.
Perlite - Expanded	**10.00**	**0.52**	**-**	Ref. 114.
Perlite - Natural	**0.66**	**0.03**	**-**	Ref. 114.
Quartz powder	**0.85**	**0.02**	**-**	Ref. 114.
Shingle	**11.30**	**0.30**	**-**	Ref. 70.
Silicon	**2355**	**-**	**-**	Ref. 167.
Slag (GGBS)	**1.60**	**0.083**	**-**	Ground Granulated Blast Furnace Slag (GGBS), economic allocation.
Silver	**128.20**	**6.31**	**-**	Ref. 148.
Straw	**0.24**	**0.01**	**-**	Refs. 63, 201, 202 & 281.
Terrazzo Tiles	**1.40**	**0.12**	**-**	Ref. 1.
Vanadium	**3710**	**228**	**-**	Ref. 22.
Vermiculite - Expanded	**7.20**	**0.52**	**-**	Ref. 114.
Vermiculite - Natural	**0.72**	**0.03**	**-**	Ref. 114.
Vicuclad	**70.00**	**-**	**-**	Ref. 1.
Water	**0.01**	**0.001**	**-**	
Wax	**52.00**	**-**	**-**	Ref. 169.
Wood stain/Varnish	**50.00**	**5.35**	**-**	Ref. 1.
Yttrium	**1470**	**84.00**	**-**	Ref. 22.
Zirconium	**1610**	**97.20**	**-**	Ref. 22.
Paint				
General	**70.00**	**2.42**	**2.91**	Large variations in data, especially for embodied carbon. Includes feedstock energy. Water based paints have a 70% market share. Water based paint has a lower embodied energy than solvent based paint.
EXAMPLE: Single Coat	**10.5 MJ/Sqm**	**0.36 kgCO2/Sqm**	**0.44**	Assuming 6.66 Sqm Coverage per kg
EXAMPLE: Double Coat	**21.0 MJ/Sqm**	**0.73 kgCO2/Sqm**	**0.87**	Assuming 3.33 Sqm Coverage per kg
EXAMPLE: Triple Coat	**31.5 MJ/Sqm**	**1.09 kgCO2/Sqm**	**1.31**	Assuming 2.22 Sqm Coverage per kg

INVENTORY OF CARBON & ENERGY (ICE) SUMMARY

Materials	Embodied Energy & Carbon Coefficients			Comments
	EE - MJ/kg	EC - kgCO2/kg	EC - kgCO2e/kg	EE = Embodied Energy, EC = Embodied Carbon
Waterborne Paint	59.00	2.12	2.54	Waterborne paint has a 70% of market share. Includes feedstock energy.
Solventborne Paint	97.00	3.13	3.76	Solventborne paint has a 30% share of the market. Includes feedstock energy. It was difficult to estimate carbon emissions for Solventborne paint.
Paper				
Paperboard (General for construction use)	24.80	1.29	-	Excluding calorific value (CV) of wood, excludes carbon sequestration/biogenic carbon storage.
Fine Paper	28.20	1.49	-	Excluding CV of wood, excludes carbon sequestration
EXAMPLE: 1 packet A4 paper	70.50	3.73	-	Standard 80g/sqm printing paper, 500 sheets a pack. Doesn't include printing.
Wallpaper	36.40	1.93	-	
Plaster				

INVENTORY OF CARBON & ENERGY (ICE) SUMMARY

Materials	Embodied Energy & Carbon Coefficients			Comments
	EE - MJ/kg	EC - kgCO2/kg	EC - kgCO2e/kg	EE = Embodied Energy, EC = Embodied Carbon
General (Gypsum)	1.80	0.12	0.13	Problems selecting good value, inconsistent figures, West et al believe this is because of past aggregation of EE with cement
Plasterboard	6.75	0.38	0.39	See Ref [WRAP] for further info on GWP data, including disposal impacts which are significant for Plasterboard.
Plastics	Main data source: Plastics Europe (www.plasticseurope.org) ecoprofiles			
General	80.50	2.73	3.31	35.6 MJ/kg Feedstock Energy (Included). Determined by the average use of each type of plastic used in the European construction industry.
ABS	95.30	3.05	3.76	48.6 MJ/kg Feedstock Energy (Included)
General Polyethylene	83.10	2.04	2.54	54.4 MJ/kg Feedstock Energy (Included). Based on average consumption of types of polyethylene in European construction
High Density Polyethylene (HDPE) Resin	76.70	1.57	1.93	54.3 MJ/kg Feedstock Energy (Included). Doesn't include the final fabrication.
HDPE Pipe	84.40	2.02	2.52	55.1 MJ/kg Feedstock Energy (Included)
Low Density Polyethylene (LDPE) Resin	78.10	1.69	2.08	51.6 MJ/kg Feedstock Energy (Included). Doesn't include the final fabrication
LDPE Film	89.30	2.13	2.60	55.2 MJ/kg Feedstock Energy (Included)
Nylon (Polyamide) 6 Polymer	120.50	5.47	9.14	38.6 MJ/kg Feedstock Energy (Included). Doesn't include final fabrication. Plastics Europe state that two thirds of nylon is used as fibres (textiles, carpets…etc) in Europe and that most of the remainder as injection mouldings. Dinitrogen monoxide and methane emissions are very significant contributors to GWP.
Nylon (polyamide) 6,6 Polymer	138.60	6.54	7.92	50.7 MJ/kg Feedstock Energy (Included). Doesn't include final fabrication (i.e. injection moulding). See comments for Nylon 6 polymer.
Polycarbonate	112.90	6.03	7.62	36.7 MJ/kg Feedstock Energy (Included). Doesn't include final fabrication.
Polypropylene, Orientated Film	99.20	2.97	3.43	55.7 MJ/kg Feedstock Energy (Included).
Polypropylene, Injection Moulding	115.10	3.93	4.49	54 MJ/kg Feedstock Energy (Included). If biomass benefits are included the CO2 may reduce to 3.85 kgCO2/kg, and GWP down to 4.41 kg CO2e/kg.
Expanded Polystyrene	88.60	2.55	3.29	46.2 MJ/kg Feedstock Energy (Included)
General Purpose Polystyrene	86.40	2.71	3.43	46.3 MJ/kg Feedstock Energy (Included)
High Impact Polystyrene	87.40	2.76	3.42	46.4 MJ/kg Feedstock Energy (Included)
Thermoformed Expanded Polystyrene	109.20	3.45	4.39	49.7 MJ/kg Feedstock Energy (Included)
Polyurethane Flexible Foam	102.10	4.06	4.84	33.47 MJ/kg Feedstock Energy (Included). Poor data availability for feedstock energy
Polyurethane Rigid Foam	101.50	3.48	4.26	37.07 MJ/kg Feedstock Energy (Included). Poor data availability for feedstock energy
PVC General	77.20	2.61	3.10	28.1 MJ/kg Feedstock Energy (Included). Based on market average consumption of types of PVC in the European construction industry
PVC Pipe	67.50	2.56	3.23	24.4 MJ/kg Feedstock Energy (Included). If biomass benefits are included the CO2 may reduce to 2.51 kgCO2/kg, and GWP down to 3.23 kg CO2e/kg.
Calendered Sheet PVC	68.60	2.61	3.19	24.4 MJ/kg Feedstock Energy (Included). If biomass benefits are included the CO2 may reduce to 2.56 kgCO2/kg, and GWP down to 3.15 kg CO2e/kg.
PVC Injection Moulding	95.10	2.69	3.30	35.1 MJ/kg Feedstock Energy (Included). If biomass benefits are included the CO2 may reduce to 2.23 kgCO2/kg, and GWP down to 2.84 kg CO2e/kg.
UPVC Film	69.40	2.57	3.16	25.3 MJ/kg Feedstock Energy (Included)
Rubber				
General	91.00	2.66	2.85	40 MJ/kg Feedstock Energy (Included)
Sand				
General	0.081	0.0048	0.0051	Estimated from real UK industrial fuel consumption data
Sealants and adhesives				
Epoxide Resin	137.00	5.70	-	42.6 MJ/kg Feedstock Energy (Included). Source: www.plasticseurope.org
Mastic Sealant	62 to 200	-	-	
Melamine Resin	97.00	4.19	-	Feedstock energy 18 MJ/kg - estimated from Ref 34.
Phenol Formaldehyde	88.00	2.98	-	Feedstock energy 32 MJ/kg - estimated from Ref 34.
Urea Formaldehyde	70.00	2.76	-	Feedstock energy 18 MJ/kg - estimated from Ref 34.
Soil				
General (Rammed Soil)	0.45	0.023	0.024	
Cement stabilised soil @ 5%	0.68	0.060	0.061	Assumed 5% cement content.
Cement stabilised soil @ 8%	0.83	0.082	0.084	Assumed 8% stabiliser content (6% cement and 2% lime).
GGBS stabilised soil	0.65	0.045	0.047	Assumed 8% stabiliser content (8% GGBS and 2% lime).
Fly ash stabilised soil	0.56	0.039	0.041	Assumed 10% stabiliser content (8% fly ash and 2% lime).

INVENTORY OF CARBON & ENERGY (ICE) SUMMARY

Materials	Embodied Energy & Carbon Coefficients			Comments
	EE - MJ/kg	**EC - kgCO2/kg**	**EC - kgCO2e/kg**	**EE = Embodied Energy, EC = Embodied Carbon**
Steel	Main data source: International Iron & Steel Institute (IISI) LCA studies (www.worldsteel.org)			
UK (EU) STEEL DATA - EU average recycled content - See material profile (and Annex on recycling methods) for usage guide				
General - UK (EU) Average Recycled Content	**20.10**	**1.37**	**1.46**	EU 3-average recycled content of 59%. Estimated from UK's consumption mixture of types of steel (excluding stainless). **All data doesn't include the final cutting of the steel products to the specified dimensions or further fabrication activities.** Estimated from World Steel Association (Worldsteel) LCA data.
Virgin	35.40	2.71	2.89	
Recycled	9.40	0.44	0.47	Could not collect strong statistics on consumption mix of recycled steel.
Bar & rod - UK (EU) Average Recycled Content	**17.40**	**1.31**	**1.40**	EU 3-average recycled content of 59%
Virgin	29.20	2.59	2.77	
Recycled	8.80	0.42	0.45	
Coil (Sheet) - UK (EU) Average Recycled Content	**18.80**	**1.30**	**1.38**	Effective recycled content because recycling route is not typical. EU 3-average recycled content of 59%
Virgin	32.80	2.58	2.74	
Recycled	Not Typical Production Route			
Coil (Sheet), Galvanised - UK (EU) Average Recycled Content	**22.60**	**1.45**	**1.54**	Effective recycled content because recycling route is not typical. EU 3-average recycled content of 59%
Virgin	40.00	2.84	3.01	
Engineering steel - Recycled	**13.10**	**0.68**	**0.72**	
Pipe- UK (EU) Average Recycled Content	**19.80**	**1.37**	**1.45**	Effective recycled content because recycling route is not typical. EU 3-average recycled content of 59%
Virgin	34.70	2.71	2.87	
Recycled	Not Typical Production Route			
Plate- UK (EU) Average Recycled Content	**25.10**	**1.55**	**1.66**	Effective recycled content because recycling route is not typical. EU 3-average recycled content of 59%
Virgin	45.40	3.05	3.27	
Recycled	Not Typical Production Route			
Section- UK (EU) Average Recycled Content	**21.50**	**1.42**	**1.53**	
Virgin	38.00	2.82	3.03	
Recycled	10.00	0.44	0.47	
Wire - Virgin	**36.00 (?)**	**2.83 (?)**	**3.02**	
Stainless	**56.70**	**6.15**		World average data from the Institute of Stainless Steel Forum (ISSF) life cycle inventory data. Selected data is for the most popular grade (304). Stainless steel does not have separate primary and recycled material production routes.
OTHER STEEL DATA - 'R.O.W' and 'World' average recycled contents - See material profile (and Annex on recycling methods) for usage guide				
General - R.O.W. Avg. Recy. Cont.	26.20	1.90	2.03	Rest of World (non-E.U.) consumption of steel. 3 year average recycled content of 35.5%.
General - World Avg. Recy. Cont.	25.30	1.82	1.95	Whole world 3 year average recycled content of 39%.
Bar & rod- R.O.W. Avg. Recy. Cont.	22.30	1.82	1.95	Comments above apply. See material profile for further information.
Bar & rod - World Avg. Recy. Cont.	21.60	1.74	1.86	
Coil - R.O.W. Avg. Recy. Cont.	24.40	1.81	1.92	
Coil - World Avg. Recy. Cont.	23.50	1.74	1.85	
Coil, Galvanised - R.O.W. Avg. Recy. Cont.	29.50	2.00	2.12	
Coil, Galvanised - World Avg. Recy. Cont.	28.50	1.92	2.03	
Pipe - R.O.W. Avg. Recy. Cont.	25.80	1.90	2.01	
Pipe - World Avg. Recy. Cont.	24.90	1.83	1.94	
Plate - R.O.W. Avg. Recy. Cont.	33.20	2.15	2.31	
Plate - World Avg. Recy. Cont.	32.00	2.06	2.21	
Section - R.O.W. Avg. Recy. Cont.	28.10	1.97	2.12	
Section - World Avg. Recy. Cont.	27.10	1.89	2.03	
Stone	Data on stone was difficult to select, with high standard deviations and data ranges.			
General	**1.26 (?)**	**0.073 (?)**	**0.079**	ICE database average (statistic), uncertain. See material profile.
Granite	**11.00**	**0.64**	**0.70**	Estimated from Ref 116.
Limestone	**1.50**	**0.087**	**0.09**	Estimated from Ref 188.
Marble	**2.00**	**0.116**	**0.13**	
Marble tile	**3.33**	**0.192**	**0.21**	Ref. 40.
Sandstone	**1.00 (?)**	**0.058 (?)**	**0.06**	Uncertain estimate based on Ref. 262.
Shale	**0.03**	**0.002**	**0.002**	
Slate	**0.1 to 1.0**	**0.006 to 0.058**	**0.007 to 0.063**	Large data range
Timber	Note: These values were difficult to estimate because timber has a high data variability. These values exclude the energy content of the wooden product (the Calorific Value (CV) from burning). See the material profile for guidance on the new data structure for embodied carbon (i.e. split into foss and bio)			
General	**10.00**	$0.30_{fos}+0.41_{bio}$	$0.31_{fos}+0.41_{bio}$	Estimated from UK consumption mixture of timber products in 2007 (Timber Trade Federation statistics). Includes 4.3 MJ bio-energy. All values do not include the CV of timber product and exclude carbon storage.
Glue Laminated timber	**12.00**	$0.39_{fos}+0.45_{bio}$	$0.42_{fos}+0.45_{bio}$	Includes 4.9 MJ bio-energy.
Hardboard	**16.00**	$0.54_{fos}+0.51_{bio}$	$0.58_{fos}+0.51_{bio}$	Hardboard is a type of fibreboard with a density above 800 kg/m3. Includes 5.6 MJ bio-energy.
Laminated Veneer Lumber	**9.50**	$0.31_{fos}+0.32_{bio}$	$0.33_{fos}+0.32_{bio}$	Ref 150. Includes 3.5 MJ bio-energy.
MDF	**11 (?)**	$0.37_{fos}+0.35_{bio}$	$0.39_{fos}+0.35_{bio}$	Wide density range (350-800 kg/m3). Includes 3.8 MJ bio-energy.
Oriented Strand Board (OSB)	**15.00**	$0.42_{fos}+0.54_{bio}$	$0.45_{fos}+0.54_{bio}$	Estimated from Refs. 103 and 150. Includes 5.9 MJ bio-energy.
Particle Board	**14.50**	$0.52_{fos}+0.32_{bio}$	$0.54_{fos}+0.32_{bio}$	Very large data range, difficult to select appropriate values. Modified from CORRIM reports. Includes 3.2 MJ bio-energy (uncertain estimate).
Plywood	**15.00**	$0.42_{fos}+0.65_{bio}$	$0.45_{fos}+0.65_{bio}$	Includes 7.1 MJ bio-energy.
Sawn Hardwood	**10.40**	$0.23_{fos}+0.63_{bio}$	$0.24_{fos}+0.63_{bio}$	It was difficult to select values for hardwood, the data was estimated from the CORRIM studies (Ref. 88). Includes 6.3 MJ bio-energy.
Sawn Softwood	**7.40**	$0.19_{fos}+0.39_{bio}$	$0.20_{fos}+0.39_{bio}$	Includes 4.2 MJ bio-energy.

INVENTORY OF CARBON & ENERGY (ICE) SUMMARY

Materials	Embodied Energy & Carbon Coefficients			Comments
	EE - MJ/kg	EC - kgCO2/kg	EC - kgCO2e/kg	EE = Embodied Energy, EC = Embodied Carbon
Veneer Particleboard (Furniture)	**23$_{(fos + bio)}$**	**(?)**	**(?)**	Unknown split of fossil based and biogenic fuels.
Tin				
Tin Coated Plate (Steel)	**19.2 to 54.7**	**1.04 to 2.95**	**-**	
Tin	**250.00**	**13.50**	**14.47**	lack of modern data, large data range
Titanium				
Virgin	**361 to 745**	**19.2 to 39.6 (??)**	**20.6 to 42.5 (??)**	lack of modern data, large data range, small sample size
Recycled	**258.00**	**13.7 (??)**	**14.7 (??)**	lack of modern data, large data range, small sample size
Vinyl Flooring				
General	**68.60**	**2.61**	**3.19**	23.58 MJ/kg Feedstock Energy (Included), Same value as PVC calendered sheet. *Note: the book version of ICE contains the wrong values. These values are up to date*
Vinyl Composite Tiles (VCT)	**13.70**	**-**	**-**	Ref. 94.
Zinc				
General	**53.10**	**2.88**	**3.09**	Uncertain carbon estimates, currently estimated from typical UK industrial fuel mix. Recycled content of general Zinc 30%.
Virgin	72.00	3.90	4.18	
Recycled	9.00	0.49	0.52	

INVENTORY OF CARBON & ENERGY (ICE) SUMMARY

Materials	Embodied Energy & Carbon Coefficients			Comments
	EE - MJ/kg	EC - kgCO2/kg	EC - kgCO2e/kg	EE = Embodied Energy, EC = Embodied Carbon

Miscellaneous (No material profiles):

	Embodied Energy - MJ	Embodied Carbon - Kg CO2		
PV Modules	MJ/sqm	Kg CO2/sqm		
Monocrystalline	**4750 (2590 to 8640)**	**242 (132 to 440)**	-	Embodied carbon estimated from typical UK industrial fuel mix. This is not an ideal method.
Polycrystalline	**4070 (1945 to 5660)**	**208 (99 to 289)**	-	
Thin Film	**1305 (775 to 1805)**	**67 (40 to 92)**	-	
Roads	Main data source: ICE reference number 147			
Asphalt road - Hot construction method - 40 yrs	**2,509 MJ/Sqm**	**93 KgCO2/Sqm**	**99 KgCO2/Sqm**	730 MJ/Sqm Feedstock Energy (Included). For more detailed data see reference 147. (Swedish study). The data in this report was modified to fit within the ICE framework. Includes all sub-base layers to construct a road. Sum of construction, maintenance, operation.
Construction	1,069 MJ/Sqm	30.9 KgCO2/Sqm	32.8 KgCO2/Sqm	480 MJ/Sqm Feedstock Energy (Included)
Maintenance - 40 yrs	471 MJ/Sqm	11.6 KgCO2/Sqm	12.3 KgCO2/Sqm	250 MJ/Sqm Feedstock Energy (Included)
Operation - 40 yrs	969 MJ/Sqm	50.8 KgCO2/Sqm	54.0 KgCO2/Sqm	Swedish scenario of typical road operation, includes street and traffic lights (95% of total energy), road clearing, sweeping, gritting and snow clearing.
Asphalt road - Cold construction method - 40 yrs	**3,030 MJ/Sqm**	**91 KgCO2/Sqm**	**97 KgCO2/Sqm**	1,290 MJ/kg Feedstock Energy (Included). Sum of construction, maintenance, operation.
Construction	825 MJ/Sqm	26.5 KgCO2/Sqm	28.2 KgCO2/Sqm	320 MJ/Sqm Feedstock Energy (Included)
Maintenance - 40 yrs	1,556 MJ/Sqm	13.9 KgCO2/Sqm	14.8 KgCO2/Sqm	970 MJ/Sqm Feedstock Energy (Included)
Operation - 40 yrs	969 MJ/Sqm	50.8 KgCO2/Sqm	54.0 KgCO2/Sqm	See hot rolled asphalt.
Concrete road - 40 yrs	**2,084 MJ/Sqm**	**142 KgCO2/Sqm**	-	Sum of construction, maintenance, operation.
Construction	885 MJ/Sqm	77 KgCO2/Sqm	-	
Maintenance - 40 yrs	230 MJ/Sqm	14.7 KgCO2/Sqm	-	
Operation - 40 yrs	969 MJ/Sqm	50.8 KgCO2/Sqm	-	Swedish scenario of typical road operation, includes street and traffic lights (95% of total energy), and also road clearing, sweeping, gritting and snow clearing.

Note: *The above data for roads were based on a single reference (ref 145). There were other references available but it was not possible to process the reports into useful units (per sqm). One of the other references indicates a larger difference between concrete and asphalt roads than the data above. If there is a particular interest in roads the reader is recommended to review the literature in further detail.*

Windows	MJ per Window			
1.2mx1.2m Single Glazed Timber Framed Unit	**286 (?)**	**14.6 (?)**	-	Embodied carbon estimated from typical UK industrial fuel mix
1.2mx1.2m Double Glazed (Air or Argon Filled):	--	--	-	--
Aluminium Framed	**5470**	**279**	-	
PVC Framed	**2150 to 2470**	**110 to 126**	-	
Aluminium -Clad Timber Framed	**950 to 1460**	**48 to 75**	-	
Timber Framed	**230 to 490**	**12 to 25**	-	
			-	
Krypton Filled Add:	**510**	**26**	-	
Xenon Filled Add:	**4500**	**229**	-	

NOTE: Not all of the data could be converted to full GHG's. It was estimated from the fuel use only (i.e. Not including any process related emissions) the full CO2e is approximately 6 percent higher than the CO2 only value of embodied carbon. This is for the average mixture of fuels used in the UK industry.

REFERENCES

Ref No.	Title	Author	Year	Organisation/Publisher	ISBN
1	A comparative Environmental Life Cycle Assessment of Modern Office Buildings	K J Eaton & A Amato	1998	The Steel Construction Institute	1859420583
2	A comparative LCA of building insulation products made of stone wool, paper wool and flax	Anders Schmidt, Allan Jensen et al.	2004	International Journal of LCA	
3	A Comparison of the Embodied and operational Environmental impacts of insulation in Office Buildings	Mark Lucuik	2005	10th Canadian Conference on Building Science and Technology, Ottawa, May 2005	
4	A decision making matrix with life cycle perspective of materials for roofs in Sri Lanka	U G Yasantha Abeysundra, Sandhya Babel, Shabbir Gheewala	2006	Materials and Design 2006, article in press, doi:10.1016/j.matdes.2006.09.011	
5	A life cycle analysis of the environmental impacts of asphalt and concrete roads	Gianni Pontarollo & Tim Smith	2001	IRF world road congress 2001	
6	A life cycle assessment and evaluation of construction and demolition waste	Amelia Craighill & Jane Powell	1999	The Centre for Social and Economic Research on the Global Environment (CSERGE)	
7	A material flow analysis and an ecological footprint of the southeast region, chapter 3	John Barrett et al	2002	Taking stock, Biffaward	
8	Acrylonitrile-Butadiene-Styrene Copolymer (ABS) LCI Data Summary	I Boustead	2005	APME, Association of Plastics Manufacturers in Europe	
9	Acrylonitrile-Butadiene-Styrene Copolymer (ABS) LCI Data Summary in Excel Format	I Boustead	2005	APME, Association of Plastics Manufacturers in Europe	
10	Aluminium applications and society, paper 1 automotive, expanded summary	International primary aluminium institute	2000	International primary aluminium institute	
11	An ecological assessment of the vernacular architecture and of its embodied energy in Yunnan, China	Wang Renping, Cai Zhenyu	2006	Building and environment 41, 2006, pg 687-697	
12	An energy life cycle assessment model for building design	Jorn Dinesen & Steen Traberg-Borup	1994	Danish Building research institute (SBI). Proceedings of the CIB conference on buildings and the environment.	
13	An environmental comparison of bridge forms	D Collings	2006	Bridge Engineering, 159, December 2006, Issue BE4, Pg 163-168	
14	Approved Environmental Profile, Manufacture of 1 tonne Ground Granulated Blastfurnace Slag	BRE Environmental Profiles	2006	BRE	
15	Assessing the environmental impact of metal production processes	T E norgate, S Jahanshahi, W J Rankin	2006	Journal of Cleaner Production 15, 2007, Pg 838-848	
16	Assessment of the automotive assembly paint process for energy, environmental and economic improvement	Geoffrey J Roelant, Amber J Kemppainen and david R Shonnard	2004	Journal of Industrial Ecology, Volume 8, Number 1-2	
17	Assessment of the decrease of CO2 emissions in the construction field through the selection of materials: Practical case study of three houses of low environmental impact	Maria Jesus Gonzalez, Justo Garcia Navarro	2005	Building And Environment; Article in press	
18	Australian LCA data - SimaPro Data	RMIT Uni, Victoria University Australia	1998	RMIT Uni, Victoria University Australia	
19	Background document for life cycle greenhouse gas emission factors for carpet and personal computers	US environment Protection Agency	2003	US environment Protection Agency	
20	Background Document for Life-Cycle Greenhouse Gas Emission Factors for Carpet and Personal Computers	US environmental protection agency	2003	US environmental protection agency	
21	Best Available Techniques for the Cement Industry	Cembureau	1999	cembureau	
22	Birth to death analysis of the energy payback ratio and CO2 gas emission rates from coal, fission, wind and DT-fusion electrical power plants	Scott W White and Gerald L Kulcinski	2000	Fusion engineering and design 48, 2000, Pg 473-481	
23	Building energy performance: A LCA case study of kenaf-fibres insulation board	Fulvio Ardente, Marco Beccali, Maurizio Cellura, Marina Mistretta	2008	Energy and Buildings 40 (2008) 1–10	
24	Building materials energy and the environment: Towards ecologically sustainable development	Bill Lawson	1996	The Royal Australian Institute of Architects	1863180230
25	Building Research Establishment (BRE) environmental profiles - Clay tiles	Building Research Establishment (BRE)	1996	Building Research Establishment (BRE)	
26	Building Research Establishment (BRE) Environmental profiles - Glass wool	Building Research Establishment (BRE)	1999	Building Research Establishment (BRE)	
27	Building Research Establishment (BRE) environmental profiles - UK kiln dried timber (softwood)	Building Research Establishment (BRE)	1996	Building Research Establishment (BRE)	
28	Building the Environmental Performance of UK Forest Products into Construction	J S Mundy and P W Bonfield	2000	BRE	
29	Bulk polymerised PVC LCI Data Summary	I Boustead	1999	APME, Association of Plastics Manufacturers in Europe	
30	Bulk polymerised PVC LCI Data Summary in Excel	I Boustead	1999	APME, Association of Plastics Manufacturers in Europe	
31	Ceramic Floor and Wall Tile: An Ecological Building Material	Giorgio Timellini, Carlo Palmonari & Alberto Fregni	2005	Tile Today, Issue 46	
32	Characterization of automotive paints: an environmental impact analysis	Stella Papasavva, Sheila Kia, Joseph Claya, Raymond Gunther	2001	Progress in Organic Coatings 43 (2001) 193–206	
33	CIBSE Guide A: Environmental Design	Chartered institute of Building Service Engineers (CIBSE)	2006	Chartered institute of Building Service Engineers (CIBSE)	1903287669
34	Closing Carbon Cycles, Chapter 4 - Gross energy requirements (GER) and gross CO2 emissions for products of the organic chemical industry	Martin Patel, E Jochem	1999	Utrecht university, The Netherlands	
35	CO2 emissions of the Swedish steel industry	Hans Sandberg, Rune Lagneborg et al	2001	Scandinavian Journal of Metallurgy	
36	Comparative analysis of available life cycle inventories of cement in the EU	Alejandro Josa, Antonio Aguado, Atte Heino, Ewan Byars and Arnaldo Carmin	2002	Cement and concrete journal 34 (2004) published by Peragmon, Elsevier	
37	Comparative Analysis of Embodied Energy Rates for Walling Elements in India	P S Chani, Najamuddin & S K Kaushik	2003	Journal of the Institution of Engineers (India)	
38	Comparative energy evaluation of plastic products and their alternatives for the building and construction and transportation industries	Franklin Associates	1991	The Society of the plastics industry	
39	Comparative environmental life cycle assessment of composite materials	O M De Vegt & W G Haije	1997	unknown, reference number ECN-I-97-050	
40	Comparative Life Cycle Assessment of Flooring Materials: Ceramic versus Marble Tile	Giuseppe M. Nicoletti a, Bruno Notarnicola & Giuseppe Tassielli	2000	Journal of Cleaner Production; 10, 2002, pg 283-296	
41	Comparative Life Cycle Assessment of Three Insulation Materials: Stone Wool, Flax and Paper Wool	Anders Schmidt, Anders Ulf Clausen, Allan Astrup Jensen, and Ole Kamstrup	2003	LCA Documents 8, Eco-Informa Press	3-928379-60-7
42	Comparing energy use and environmental emissions of reinforced wood doors and steel doors	Lynn knight, Melissa Huff, Janet I Stockhausen & Robert J Ross	2005	Forest Products Journal, June 2005, Vol 55, No 6	
43	Comparison of environmental impacts of two residential heating systems	Lijun Yang, Radu Zmeureanu & Huges Rivard	2007	Article in Press, Building and Environment, doi:10.1016/j.buildenv.2007.02.007	
44	Concrete building blocks made with recycled demolition aggregate	M N Soutsos, S G Millard, J H Bungey	2006	Concrete Plant International, August 2006	
45	Concrete with Ceramic Waste Aggregate	R M Senthamarai and P Devadas Manoharan	2005	Cement & Concrete Composites	
46	Confederation of paper industries web address: http://www.paper.org.uk/	Confederation of paper industries	2005	Confederation of the paper industries	
47	Conservation of energy and natural resources by recycling building waste	C Thormark	2001	Resources Conservation & Recycling	
48	Conversion processes for polyolefin's	I Boustead	2003	APME, Association of Plastics Manufacturers in Europe	
49	Copper Environmental Profile	Kennecott Utah Copper Corporation	2004	Kennecott Utah Copper Corporation	
50	Cradle-to-Gate Study of Red Clay for Use in the Ceramic Industry	María-Dolores Bovea, Úrsula Saura, Jose Luis Ferrero and Josep Giner	2007	International Journal of LCA 12 (6) 439 – 447. DOI: http://dx.doi.org/10.1065/lca2006.06.252	
51	Data needed for environmental assessment of building projects	Hanne Krogh and klaus Hansen	1994	Danish Building research institute (SBI). Proceedings of the CIB conference on buildings and the environment.	
52	Defining and Improving Environmental Performance in the Concrete Industry	D Higgins, L Parrott & L Sear	2000	DETR & UK Concrete Alliance	

REFERENCES

Ref No.	Title	Author	Year	Organisation/Publisher	ISBN
53	ECFA Environmental Declaration Plasticising Admixtures	ECFA - European Federation of Concrete Admixture Association	2006	ECFA - European Federation of Concrete Admixture Association	
54	Ecohouse 2: A Design Guide	Sue Roaf, Manuel Fuentes & Stephanie Thomas	2003	Architectural Press (Elsevier)	750657340
55	Ecology of Building Materials	Bjorn Berge	2000	Architectural press	750633948
56	ECO-Profiles of the European Plastics Industry, Methodology	I Boustead	2003	APME, Association of Plastics Manufacturers in Europe	
57	EEE: A prototype tool for the evaluation of embodied energy and greenhouse gas emissions of exterior envelope of Canadian houses	Rym Baouendi, Radu Zmeureanu, Brian Bradley & Avi Friedman	2002	Centre for Building Studies, Department of Building, Civil and Environmental Engineering, Concordia University, Montreal, Quebec, Canada	
58	Embodied CO_2 of factory made cements and combinations, fact sheet 18 (P2)	Chris Clear, Denis Higgins and Lindon Sear	2009	British Cement Association (BCA)	
59	Embodied CO_2 of UK cement, additions and cementitious material, fact sheet 18 (P1)	Chris Clear, Denis Higgins and Lindon Sear	2009	British Cement Association (BCA)	
60	Embodied energy - detailed methodology	Tim Grant at the Centre for Design at RMIT	2001	Centre for Design RMIT University Australia	
61	Embodied energy analysis of New Zealand building materials	Alcorn and Baird	1996	Embodied Energy - The Current State of Play, Deakin University, Nov 1996	
62	Embodied energy and carbon dioxide emissions for building materials	John West, Carol Atkinson & Nigel Howard	1994	Proceedings of the CIB conference on buildings and the environment, BRE	
63	Embodied Energy and CO2 Coefficients for NZ Building Materials	Andrew Alcorn	2003	Centre for Building Performance Research, Victoria University of Wellington	
64	Embodied Energy and CO2 Emissions of Wood and Concrete Framed Buildings in Sweden	L Gustavsson & R Sathre	2004	Ecotechnology, Mid-Sweden university	
65	Embodied Energy Coefficients of Building Materials	Andrew Alcorn	1996	Centre for Building Performance Research, Victoria University of Wellington	
66	Embodied energy in buildings: Wood versus concrete - reply to Borjesson and Gustavsson	M Lenzen and G Treloar	2002	Energy Policy 30, 2002, 249-255	
67	Embodied energy of common and alternative building materials and technologies	B V Venkaarama Reddy & K S Jagadish	2001	Energy and buildings, Elsevier	
68	Energy Analysis	Edited by John A G Thomas	1977	IPC science Press Technology	902852604
69	Energy and environmental impact analysis of double-glazed windows	G Weir and T Muneer	1996	Napier university	
70	Energy consumption and associated greenhouse gas emissions related to maintenance of a residential structure	Paul Winistorfer & Zhangjing Chen	2004	CORRIM	
71	Energy consumption of asphalt and reinforced concrete pavement materials and construction	Pablo Zapata & John Gambatese	2005	Journal of infrastructure systems, March 2005	
72	Energy Performance of buildings	George Baird, Michael R Donn	1984	CRC Press Inc.	849351863
73	Energy use during the life cycle of buildings: a method	K Adalberth	1997	Building and environment, Vol 32, No. 4, pg 317-320	
74	Environmental assessment of bio-based polymers and natural fibres	Martin Patel, Catia Bastioli et al	2003	Unknown	
75	Environmental Assessment of Brick Production in Greece	Christopher Koroneos & Aris Dompros	2006	Bulding and Environment 42, 2007, Pg 2114-2123	
76	Environmental Benefits of Recycling - An international Review of Life Cycle Comparisons for Key Materials in the UK Recycling Sector	WRAP - Waste Resources Action Programme	2006	WRAP - Waste Resources Action Programme	
77	Environmental burdens of concrete and concrete products	Sirje Vares & Tarja Häkkinen	1998	Technical Research Centre of Finland, VTT Building Technology	
78	Environmental declaration of the VELFAC 200 window system according to the LCA principle (EDIP method)	Velfac	2006	Teknologisk Institut (The Danish Technological Institute)	
79	Environmental Declaration, Nordic Timber Industry, ND Security Window	Nr 310181/1- Norwegian Institute of Wood Technology	2001		
80	Environmental Fact Sheet - Elevator system Schindler 3100/3300/5300	QP 04017, Schindler	2005		
81	Environmental Fact Sheet - Elevator system Schindler 7000	QP 03060, Schindler	2003		
82	Environmental impact of building and construction materials, Volume B: Mineral products	R Clough and R Martyn	1995	CIRIA, Construction Industry Research and Information Association	860178129
83	Environmental impact of building and construction materials, Volume C: Metals	N Howard	1995	CIRIA, Construction Industry Research and Information Association	860178137
84	Environmental impact of building and construction materials, Volume D: Plastics and elastomers	R Clough and R Martyn	1995	CIRIA, Construction Industry Research and Information Association	860178145
85	Environmental impact of building and construction materials, Volume E: Timber and timber products	J Newton and R Venables	1995	CIRIA, Construction Industry Research and Information Association	860178153
86	Environmental impact of building and construction materials, Volume F: Paints and coatings, adhesives and sealants	R Bradley, A Griffiths and M Levitt	1995	CIRIA, Construction Industry Research and Information Association	860178161
87	Environmental Impact of Coated Exterior Wooden Cladding	Tarja Häkkinen, Pirjo Ahola, Leila Vanhatalo, Arja Merra	1999	VTT Building Technology	
88	Environmental Impact of producing hardwood lumber using life-cycle inventory	Richard D Bergman, Scott A Bowe	2008	Wood and Fibre Science, 40(3). Pp 448-458	
89	Environmental LCI data for Rockwool Rollbatt	Price Waterhouse Coopers, PWC	2003	Price Waterhouse Coopers, PWC	
90	Environmental Performance Evaluation of Thermal Insulation Materials and its Impact on the Building	A M Papadopoulos & E Giama	2006	Building and Environment, Article in Press, doi:10.1016/j.buildenv.2006.04.012	
91	Environmental Product Declaration (ISO DIS 21 930) Glasal	Etex - Glasal	2007		
92	Environmental Product Declaration for Steel Roof Cladding using Colorcoat HPS200	Corus	2005		
93	Environmental product declaration of raw and melamine faced wood particleboard	SAIB S.p.A, Italy	2007		
94	Environmental Resource guide	Joseph A Demkin	1997	AIA, American institute of Architects	471140430
95	Environmental, economic and social analysis of materials for doors and windows in Sri Lanka	U G Yasantha Abeysundra, Sandhya Babel, Shabbir Gheewala & Alice Sharp	2006	Building and Environment 42, 2007, Pg 2141-2149	
96	Environmental, Health, and Safety Guidelines for Cement and Lime Manufacturing	International Finance Corporation, World Bank Group	2007	World Bank Group	
97	Epoxy resin LCI Data Summary	I Boustead	1999	APME, Association of Plastics Manufacturers in Europe	
98	Epoxy resin LCI Data Summary in excel format	I Boustead	1999	APME, Association of Plastics Manufacturers in Europe	
99	Estimate of energy consumption and CO2 emission associated with the production, use and final disposal of sheets made of PVC-P, MDPE and bituminous materials	José María Baldasano Recio, María Gonçalves Ageitos, Pedro Jiménez Guerrero	2005	Universitat Politecnica de Catalunya	
100	Estimating the embodied energy of timber building products	Stephen Pullen	2000	Journal of the institute of Wood Science, Vol 15 No.3, 2000	
101	EU ETS Phase II Benchmarks Supporting Documentation: Ceramics	Enviros Consulting Limited	2006	Enviros Consulting Limited	
102	European Database for Corrugated Board Life Cycle Studies	FEFCO European Federation of Corrugated Board Manufacturers, & GEO & ECO	2006	FEFCO European Federation of Corrugated Board Manufacturers, & GEO & ECO	
103	Eurostrand - Oriented Strand Board (OSB) - Environmental Product Declaration	Institut Bauen und Umwelt -German Institute of Construction and Environment	2005	Declaration number: AUB-EHW-10305-E	
104	Evaluate the whole life environmental impact of glass in a fully glazed commercial building	Mohamed R Kiani, Andrew Miller et al	2005	University of Brighton	
105	Evaluation of building environmental impacts: Two case studies	Stephen Carpenter & John Kokko	1996	ASHRAE transactions	
106	Evaluation of CO2 payback time of power plants by LCA	K Tahara, T Kojima, A Inaba	1997	Energy conservation and management, Vol 38	
107	Façade Panels and Level Panels - Textura / Natura, Eterplan - Environmental Product Declaration	Institut Bauen und Umwelt -German Institute of Construction and Environment	2007	Declaration number: AUB-ETE-10907-E	
108	Gate to Gate Life Cycle Inventory of Glued-Laminated Timbers Production	Maureen E Puettmann and James B Wilson	2005	Wood and Fibre Science 37, Special CORRIM Issue, 2005, Pg 99-113	

REFERENCES

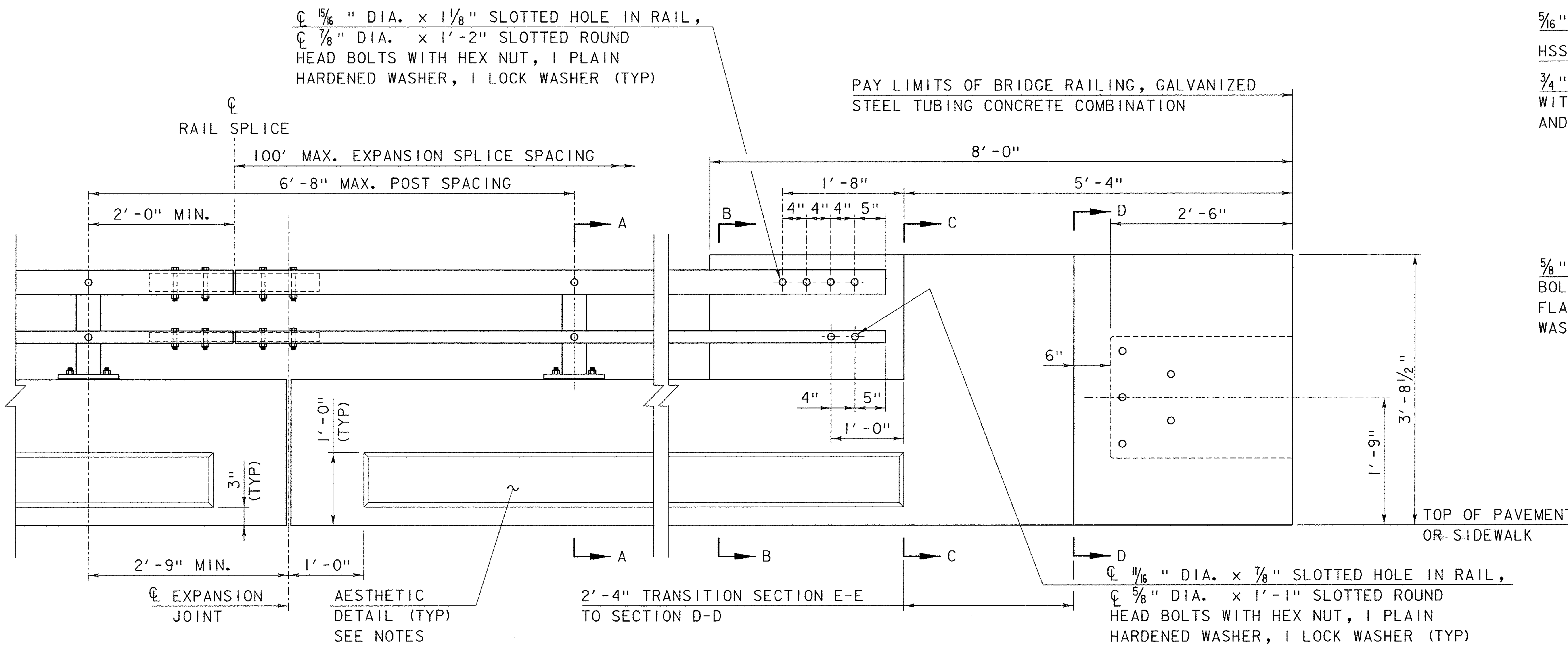
Ref No.	Title	Author	Year	Organisation/Publisher	ISBN
109	Gate to Gate Life Cycle Inventory of I-Joist Production	James B Wilson & Eric R Dancer	2005	Wood and Fibre Science 37, Special CORRIM Issue, 2005, Pg 85-98	
110	Gate to Gate Life Cycle Inventory of Laminated Veneer Lumber Production	James B Wilson & Eric R Dancer	2005	Wood and Fibre Science 37, Special CORRIM Issue, 2005, Pg 114-127	
111	Gate to gate life cycle inventory of softwood lumber production	Michael R Milota, Cynthia D West & Ian D Hartley	2005	Wood and Fibre Science, 37 Corrim Special issue, 2005, Pg 47-57	
112	Gate to Gate Life Cycle inventory of Softwood Plywood Production	James B Wilson and Eric T Sakimoto	2005	Wood and Fibre Science 37, Special CORRIM Issue, 2005, Pg 58-73	
113	Gate to Gate Life Cycle Inventory of Oriented Strandboard Production	D Earl Kline	2005	Wood and Fibre Science 37, Special CORRIM Issue, 2005, Pg 74-84	
114	GBC - The green building challenge handbook	Unknown	1995	http://www.gbc-ziegelhandbuch.org/eng/main.asp?Menu=3	
115	Glass Recycling - Lifecycle Carbon Dioxide Emissions	Prepared for British Glass by Enviros Consulting Ltd	2003	British Glass	
116	Granite Dimensional Stone Quarrying and Processing: A Life-Cycle Inventory	University of Tennessee Center for Clean Products	2008	University of Tennessee Center for Clean Products	
117	Green building Handbook Vol 2: A guide to building products and their impact on the environment	Tom Woolley, Sam Kimmins	2000	E & FN Spon, Taylor & Francis Group	419253807
118	Green Building Handbook: A guide to building products and their impact on the environment	Tom Woolley, Sam Kimmins	1997	E & FN Spon, Thomson Science & Professional	419226907
119	Greenhouse Gas Emissions and Costs Over the Life Cycle of Wood and Alternative Flooring Materials	Ann Kristin Petersen and Birger Solberg	2004	Climatic Change 64, 2004, Pg 143-167	
120	Handbook of Industrial Energy Analysis	I Boustead, G F Hancock	1979	Ellis Horwood Limited	853120641
121	High Density polyethylene LCI Data Summary	I Boustead	2005	APME, Association of Plastics Manufacturers in Europe	
122	High Density polyethylene LCI Data Summary in Excel format	I Boustead	2005	APME, Association of Plastics Manufacturers in Europe	
123	High Density polyethylene pipe extrusion LCI Data Summary	I Boustead	2005	Plastic Europe, the former APME	
124	High Density polyethylene pipe extrusion LCI Data Summary in Excel format	I Boustead	2005	APME, Association of Plastics Manufacturers in Europe	
125	High Performance High Volume Fly Ash Concrete for Sustainable Development	P Kumar Mehta	2004	international Workshop on Sustainable Development and Concrete technology, Beijing, China, May 20-21 2004	
126	How Sustainable is Concrete?	Leslie Struble and Jonathan Godfrey	1999	University of Illinois, International workshop on sustainable development and concrete technology	
127	IISF - Stainless steel LCI spreadsheet	IISF - institute of Stainless Steel Forum (ISSF)	2004	IISF - institute of Stainless Steel Forum (ISSF)	
128	IISI bar & wire rod BF route	IISI - International Iron & Steel Institute	2000	IISI - International Iron & Steel Institute	
129	IISI bar & wire rod EAF route	IISI - International Iron & Steel Institute	2000	IISI - International Iron & Steel Institute	
130	IISI coated flat steel BF route	IISI - International Iron & Steel Institute	2000	IISI - International Iron & Steel Institute	
131	IISI electrogalvanised coil BF route	IISI - International Iron & Steel Institute	2000	IISI - International Iron & Steel Institute	
132	IISI engineering steel EAF route	IISI - International Iron & Steel Institute	2000	IISI - International Iron & Steel Institute	
133	IISI Finished cold rolled coil BF route	IISI - International Iron & Steel Institute	2000	IISI - International Iron & Steel Institute	
134	IISI Hot dipped galvanised coil BF route	IISI - International Iron & Steel Institute	2000	IISI - International Iron & Steel Institute	
135	IISI Hot rolled coil BF route	IISI - International Iron & Steel Institute	2000	IISI - International Iron & Steel Institute	
136	IISI Plate BF route	IISI - International Iron & Steel Institute	2000	IISI - International Iron & Steel Institute	
137	IISI section BF route	IISI - International Iron & Steel Institute	2000	IISI - International Iron & Steel Institute	
138	IISI section EAF route	IISI - International Iron & Steel Institute	2000	IISI - International Iron & Steel Institute	
139	IISI Steel pipe BF route	IISI - International Iron & Steel Institute	2000	IISI - International Iron & Steel Institute	
140	Integrated Pollution Prevention and Control (IPPC) - Reference Document on Best Available Techniques in the Cement and Lime Manufacturing Industries	European Comission, IPPC	2001	European Comissions	
141	Integrated Pollution Prevention and Control; Draft reference document on best available techniques in the ceramic manufacturing industry, draft October 2004	European Commission	2004	European Commission	
142	Integrated Pollution Prevention and Control; Draft reference document on best available techniques in the pulp and paper manufacturing industry, December 2001	European Commission	2001	European Commission	
143	Kingspan Therma - An Environmental Profile	Kingspan	2006	Kingspan	
144	KONE MonoSpace - Environmnetal Product Declaration	VTT, Technical Research Centre of Finland	2009		
145	LCA and Embodied Energy; Some Contentious Issues	W R Lawson	1996	Embodied Energy - The Current State of Play, Deakin University, Nov 1996	
146	LCA Fact Sheet, Life Cycle Analysis of Clay Brick Housing - Based on a Typical Project Home	The Centre for Sustainable Technology, University of Newcastle, Australia	2003	The Centre for Sustainable Technology, University of Newcastle, Australia	
147	LCA of Road - A pilot study for inventory analysis	Hakan Stripple	2001	IVL Swedish Environmental Research Institute	
148	Life Cycle Analysis of a Residential Home in Michigan	Steven Blanchard and Peter Reppe	1998	Centre for Sustainable Systems, university of Michigan	
149	Life cycle analysis of wind-fuel cell integrated system	F I Kahn, K Hawboldt & M T Iqbal	2005	Renewable Energy, Vol 30, 2005, Pg 157-177	
150	Life Cycle Analysis of Wood Products: Cradle to Gate LCI of Residential Wood Building Materials	Maureen E Puettmann and James B Wilson	2005	Wood and Fibre Science 37, Special CORRIM Issue, 2005, Pg 18-29	
151	Life cycle assessment environmental profile of cotton and polyester-cotton fabrics	Eija M Kalliala & Pertti Nousiainen	1999	AUTEX Research Journal Vol 1, No. 1, 1999	
152	Life Cycle Assessment for Painting Processes: Putting the VOC Issue in Perspective	Ian D Dobson	1995	Progress in Prganic Coatings 27, 1996, Pg 55-58	
153	Life Cycle Assessment of 4 Types of Floor Covering	Jose Potting & Korenils Blok	1994	Dept. science, technology and society, Utrecht university	
154	Life cycle assessment of a car tyre	A. Kromer, E Kreipe, Diethelm Reichenbach and R. Stark	1999	Continental AG, Hannove, Germany	
155	Life cycle assessment of a wind farm and related externalities	L Schleisner	2000	Renewable energy 20, 2000, 279-288	
156	Life cycle assessment of aluminium: inventory data for the primary aluminium industry - Year 2005 update	International Aluminium Institute	2007	International Aluminium Institute	
157	Life Cycle Assessment of Copper Products	Ladji Tikana, Henrike Sievers, and Anton Klassert	2005	Deutsches Kupferinstitut – Life Cycle Centre	
158	Life Cycle Assessment of Flooring Materials: Case Study	A. Jonsson, A-M, Tillman, T.Svensson	1995	Building and Environment (Journal) Vol 32, No.3, pg 245-255, 1997, Pergamon, Elsevier.	
159	Life Cycle Assessment of Nickel Products	Ecobalance for Nickel Industry LCA Group	2000	Ecobalance for Nickel Industry LCA Group	
160	Life Cycle Assessment of Particleboards and Fibreboards	A. Frühwald, J. Hasch	1999	http://www.oekobilanzen-holz.de/	
161	Life Cycle Assessment of Plasterboard	WRAP	2008	Waste Resources Action Programme (WRAP)	
162	Life Cycle Assessment of polyvinyl Chloride and Alternatives: Summary Report for Consultation	DEFRA	2001	DEFRA, Web address: http:www.defra.gov.uk/environment/consult/PVC/index2.htm	
163	Life Cycle Assessment of PVC and of Principle Competing Materials	Martin Baitz, Johannes Kreissig and Eloise Byrne	2004	European Commission	
164	Life Cycle Assessment of Road Construction	Ulla-Maija Mroueh, Paula Eskola, Jutta Laine-Ylijoki, Kari Wellman et al	2000	FINNRA - Finnish National Road Administration	
165	Life Cycle Assessment of Wood Floor Coverings	Barbara Nebel, Bernhard Zimmer and Gerd Wegener	2006	International Journal of LCA 11 (3), 2006, Pg 172-182	
166	Life Cycle Assessments of Natural Fibre Insulation Materials	Richard J Murphy and Andrew Norton	2008	Imperial College London	
167	Life cycle CO2 emissions of a photovoltaic/wind/diesel generating system	Y Kemmoku, K Ishikawa, S Nakagawa, T Kawamoto & T S	2002	Electrical engineering in Japan, Vol 138, No. 2, 2002	
168	Life Cycle CO2 Emissions of a Photovoltaic/Wind/Diesel Generating System	Yoshishige Kemmoku, Keiko Ishikawa, Shigeyasu Nakaga	2002	Electrical Engineering in Japan, Vol 1, No 2, 2002	
169	Life cycle energy and environmental performance of a new university building modelling challenges and des	Chris Scheuer, Gregory A. Keoleian, Peter Reppe	2003	Energy and buildings 35, pg 1049-1064	

REFERENCES

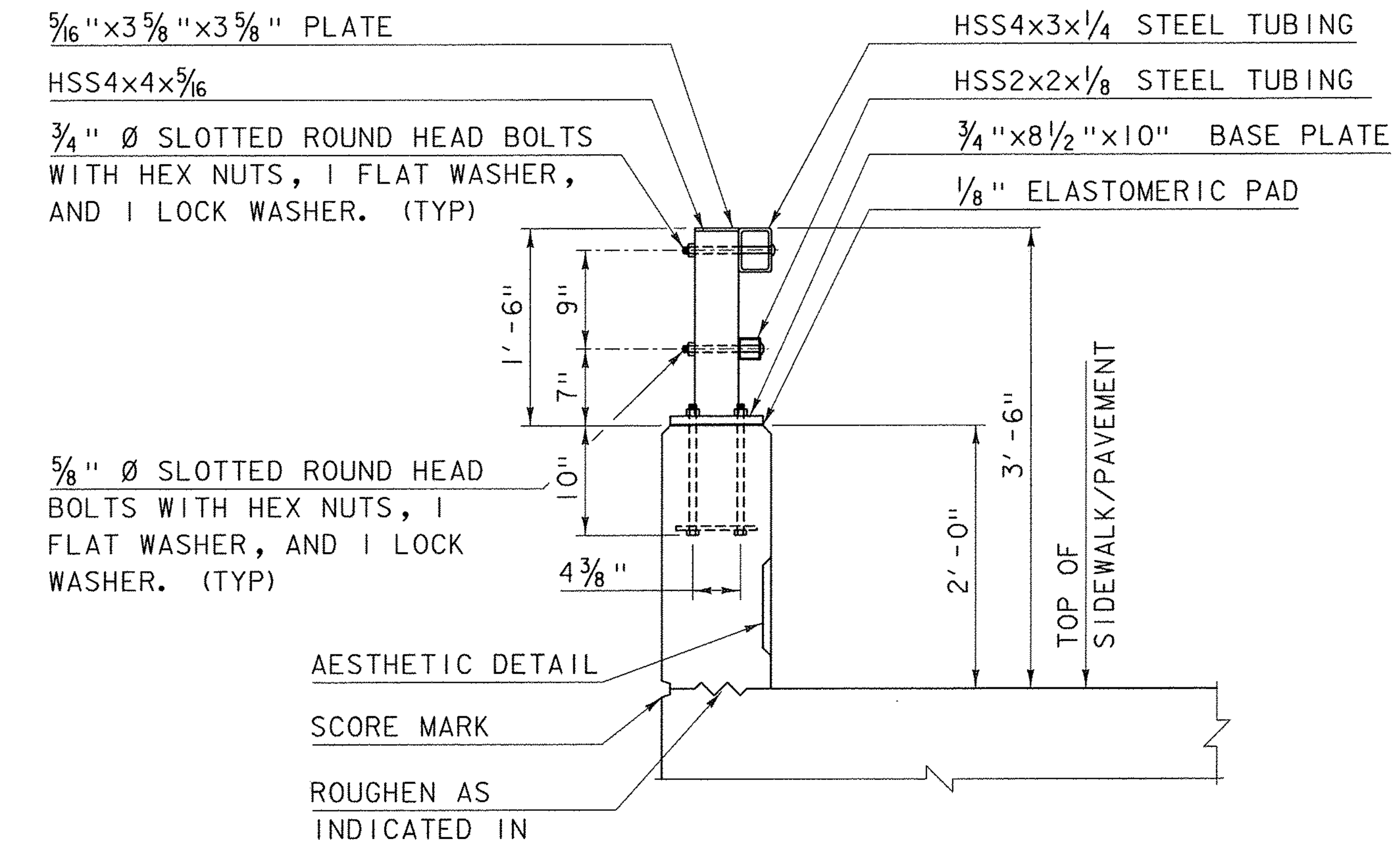
Ref No.	Title	Author	Year	Organisation/Publisher	ISBN
170	Life Cycle Environmental Assessment of Paint Processes	Stella Papasavva, Sheila Kia, Joseph Claya, and Raymon	2002	Journal of Coatings Technology, Vol. 74, No. 925, February 2002	
171	life Cycle Impact Assessment of Printing Paper using Non-Wood Pulp and De-inked Pulp	Katsuhito Nakazawa, Toru Katsura, Keiichi Katayama, Itar	2004	6th International Conference on EcoBalance, Tsukuba, Japan, 25-27 Oct. 2004.	
172	Life Cycle Inventory for kraft sack paper	Pär Weström & Cathrine Löfgre	2005	CEPI Eurokraft / Eurosac	
173	Life Cycle inventory of Five Products Produced from Polylactide (PLA) and Petroleum Based Resins - Sum	Franklin Associates for Athena Institute	2006	Athena Institute International	
174	Life Cycle inventory of Five Products Produced from Polylactide (PLA) and Petroleum Based Resins - Tech	Franklin Associates for Athena Institute	2006	Athena Institute International	
175	Life Cycle Inventory of Medium Density Fibreboard	Beatriz Rivela, M Teresa Moreira and Gumersindo Feijoo	2007	Int J LCA 12 (3) 143 – 150 (2007)	
176	Life Cycle Inventory of Particleboard: A Case Study in the Wood Sector	Beatriz Rivela, Almudena Hospido, M Teresa Moreira and	2006	International Journal of LCA 11 (2), Pg 106-113	
177	Life Cycle Inventory of Portland Cement Concrete	Medgar L. Marceau, Michael A. Nisbet, and Martha G. Var	2007	Portland Cement Association (US), illinois.	
178	Life Cycle Inventory of Slag Cement Concrete	Jan R Prusinski, Medgar L Marceau and Martha G VanGe	2003	Presented at 8th CANMET/ACI international conference in Fly Ash, Silica Fume and Natural Pozzilans in Concrete	
179	Life cycle inventory of the worldwide aluminium industry with regard to energy consumption and emissions o	International primary aluminium institute	2000	International primary aluminium institute	
180	Life cycle of window materials - A comparative assessment	M. Asif, A. Davidson & T. Muneer	2002	School of Engineering, Napier University, Edinburgh	
181	Life Cyle Assessment Data Copper Sheet	European Copper Institute	2005	European Copper Institute	
182	Life Cyle Assessment Data Copper Tube	European Copper Institute	2005	European Copper Institute	
183	Life Cyle Assessment Data Copper Wire	European Copper Institute	2005	European Copper Institute	
184	Lifecycle assessment of paint, Summary of IVL Report B 1338-A	SVEFF (TheSwedish Paint & Printing Ink MakersAssociati	1999	SVEFF (The Swedish Paint & Printing Ink Makers Association)	
185	Lightweight high-performance concrete masonry-block mix design	Babrak Amiri, Gary L Krause and Maher K Tadros	1994	ACI Materials Journal, September-October 1994	
186	Lime – A Sustainable “Green” Building Product	Wayne Kenefick and Mike Tate	2005	International Building Lime Symposium 2005, Orlando, Florida, March 9 -11, 2005	
187	Lime Activity CO2 Emissions Factors	EULA - European Lime Association	2003	EULA - European Lime Association	
188	Limestone Quarrying and Processing: A Life-Cycle Inventory	University of Tennessee	2008	University of Tennessee	
189	LISA LCA software case study, Nurses Faculty - University of Australia	LISA Software	2000	LISA Software, University of Newcastle, Australia	
190	Livscykelanalys av färg (Life cycle assessment of Paint)	Ulrik Axelsson, Anna Jarnhammar, Karl-Olof Widell, Per Jo	1999	Institutet för Vatten- och Luftvårdsforskning (IVL) report B 1338-A	
191	Loose-laid carpet tiles (PA6) - Environmental Product Declaration	Institut Bauen und Umwelt -German Institute of Constructi	2009	Declaration number: EPD-GUT-2009111-E	
192	Loose-laid carpet tiles (PA6.6) - Environmental Product Declaration	Institut Bauen und Umwelt -German Institute of Constructi	2009	Declaration number: EPD-GUT-2009411-E	
193	Low Density polyethylene film LCI Data Summary	I Boustead	2005	APME, Association of Plastics Manufacturers in Europe	
194	Low Density polyethylene film LCI Data Summary in Excel format	I Boustead	2005	APME, Association of Plastics Manufacturers in Europe	
195	Low Density polyethylene LCI Data Summary	I Boustead	2005	APME, Association of Plastics Manufacturers in Europe	
196	Low Density polyethylene LCI Data Summary in Excel format	I Boustead	1999	APME, Association of Plastics Manufacturers in Europe	
197	Materials, Operational Energy inputs and Net Energy Ratio for Photobiological Hydrogen Production	Greg Burgess, Javier Fernandez-Velasco	2006	International Journal of Hydrogen Energy, Article in Press, doi:10.1016/j.ijhydene.2006.10.055	
198	Mechanical Properties of Concrete with Recycled Coarse Aggregate	Khaldoun Rahal	2007	Building and Environment 42, 2007, Pg 407-415	
199	Metal Resources and Energy	P F Chapman, F Roberts	1983	Butterworth & Co Ltd	408108010
200	New Gross Energy Requirement Figures for Material Production	E Worrell, R J J van Heijningen et al	1993	Energy Vol 19. No.6 pg 627-640, Pergamon, Elsevier Science Ltd.	
201	New Zealand Building Materials Embodied Energy Coefficients Database: Volume II - Coefficients	Andrew Alcorn, Peter Wood	1998	Centre for Building Performance Research, Victoria University of Wellington	
202	New Zealand Embodied Energy Coefficients	George Baird, Andrew Alcorn, Phil Haslam	1997	Centre for Building Performance Research, Victoria University of Wellington	
203	Nylon 66 LCI Data Summary in Excel format, APME	I Boustead	1999	APME, Association of Plastics Manufacturers in Europe	
204	Nylon 66 LCI Data Summary, APME	I Boustead	1999	APME, Association of Plastics Manufacturers in Europe	
205	Planning for sustainable development and construction	Somerset Trust for Sustainable Development	2000	Somerset Trust for Sustainable development, Town Hall, Langport, Somerset, TA10 9GR	
206	Polyamide 6 (Nylon 6) LCI Data Summary	I Boustead	2005	APME, Association of Plastics Manufacturers in Europe	
207	Polyamide 6 (Nylon 6) LCI Data Summary in Excel	I Boustead	2005	APME, Association of Plastics Manufacturers in Europe	
208	Polyamide 66 (Nylon 66) LCI Data Summary	I Boustead	2005	APME, Association of Plastics Manufacturers in Europe	
209	Polyamide 66 (Nylon 66) LCI Data Summary in Excel	I Boustead	2005	APME, Association of Plastics Manufacturers in Europe	
210	Polycarbonate LCI Data Summary	I Boustead	2005	APME, Association of Plastics Manufacturers in Europe	
211	Polycarbonate LCI Data Summary in Excel format	I Boustead	2005	APME, Association of Plastics Manufacturers in Europe	
212	Polyolefin's	I Boustead	2003	APME, Association of Plastics Manufacturers in Europe	
213	Polypropylene injection moulding LCI Data Summary	I Boustead	2005	APME, Association of Plastics Manufacturers in Europe	
214	Polypropylene injection moulding LCI Data Summary in Excel format	I Boustead	1999	APME, Association of Plastics Manufacturers in Europe	
215	Polypropylene LCI Data Summary	I Boustead	2005	APME, Association of Plastics Manufacturers in Europe	
216	Polypropylene LCI Data Summary in Excel format	I Boustead	2005	APME, Association of Plastics Manufacturers in Europe	
217	Polypropylene orientated film LCI Data Summary	I Boustead	2005	APME, Association of Plastics Manufacturers in Europe	
218	Polypropylene orientated film LCI Data Summary in Excel format	I Boustead	2005	APME, Association of Plastics Manufacturers in Europe	
219	Polystyrene (Expandable)(EPS) LCI Data Summary	I Boustead	2006	APME, Association of Plastics Manufacturers in Europe	
220	Polystyrene (Expandable)(EPS) LCI Data Summary in Excel format	I Boustead	2006	APME, Association of Plastics Manufacturers in Europe	
221	Polystyrene (General Purpose)(GPPS) LCI Data Summary	I Boustead	2006	APME, Association of Plastics Manufacturers in Europe	
222	Polystyrene (General Purpose)(GPPS) LCI Data Summary in Excel format	I Boustead	2006	APME, Association of Plastics Manufacturers in Europe	
223	Polystyrene (High Impact) LCI Data Summary	I Boustead	2005	APME, Association of Plastics Manufacturers in Europe	
224	Polystyrene (High Impact) LCI Data Summary in Excel format	I Boustead	2005	APME, Association of Plastics Manufacturers in Europe	
225	Polyurethane Flexible foam LCI Data Summary	I Boustead	2005	APME, Association of Plastics Manufacturers in Europe	
226	Polyurethane Flexible foam LCI Data Summary in Excel	I Boustead	2005	APME, Association of Plastics Manufacturers in Europe	
227	Polyurethane Rigid foam LCI Data Summary	I Boustead	2005	APME, Association of Plastics Manufacturers in Europe	
228	Polyurethane Rigid foam LCI Data Summary in Excel	I Boustead	2005	APME, Association of Plastics Manufacturers in Europe	
229	Product Comparisons Method	G D Salomonsson & M D Ambrose	1996	CSIRO Building, Construction and Engineering, Melbourne, Australia as appearing in Embodied Energy conference at Deakin Universiity 1996	
230	PVC (emulsion polymerised) LCI Data Summary	I Boustead	1999	APME, Association of Plastics Manufacturers in Europe	
231	PVC (emulsion polymerised) LCI Data Summary in Excel	I Boustead	1999	APME, Association of Plastics Manufacturers in Europe	
232	PVC Calendered Sheet LCI Summary Data	I Boustead	2005	APME, Association of Plastics Manufacturers in Europe	
233	PVC Calendered Sheet LCI Summary Data in Excel	I Boustead	2005	APME, Association of Plastics Manufacturers in Europe	
234	PVC Injection Moulding LCI Data Summary	I Boustead	2005	APME, Association of Plastics Manufacturers in Europe	

REFERENCES

Ref No.	Title	Author	Year	Organisation/Publisher	ISBN
235	PVC Injection Moulding LCI Data Summary in Excel	I Boustead	2005	APME, Association of Plastics Manufacturers in Europe	
236	PVC pipe LCI data summary	I Boustead	2005	APME, Association of Plastics Manufacturers in Europe	
237	PVC pipe LCI data summary in Excel	I Boustead	2005	APME, Association of Plastics Manufacturers in Europe	
238	PVC Unplasticised Film (UPVC Film) LCI Data Summary	I Boustead	2005	APME, Association of Plastics Manufacturers in Europe	
239	PVC Unplasticised Film (UPVC Film) LCI Data Summary in Excel	I Boustead	2005	APME, Association of Plastics Manufacturers in Europe	
240	Quality based energy contents and carbon coefficients for building materials: A System approach	W P S Dias & S P Pooliyadda	2004	Energy 29, 2004, 561-580	
241	Quantitative assessment of embodied environmental profile of building materials	Gong, Zhiqi & Zhang, Zhihui	2004	Journal of Tsinghua university, Vol. 44, No.9	
242	Quantities for ordering building materials	Cement and concrete institute	2006	Cement and Concrete Institute	
243	Quantity based Energy Contents and Carbon Coefficients for Building Materials: A Systems Approach	W P S Dias & S P Pooliyadda	2001	Energy 29, 2004, pg 561-580	
244	Quarry Products Association - Sustainable Development Report 2008	Quarry Products Association	2008	Quarry Products Association -	
245	Reducing the Carbon Footprint of Masonry Mortar	Paul Livesey	2007	The Journal of the Building Limes Forum, Volume 14, 2007	
246	Reference Document on Best Available Techniques in the Cement and Lime Manufacturing Industries	Integrated Pollution Prevention and Control, European Co	2007	Integrated Pollution Prevention and Control, European Commission	
247	Reference Document on Reference Document on the Best Available Techniques in the Ceramic Manufactu	European Comission	2007	European Comission	
248	Report for Life Cycle Assessment for Paper and Packaging Waste Management Scenarios in New South W	Tim Grant, Karli L. James, Sven Lundie, Kees Sonneveld	2001	Joint collaboration of Australian Universities, Centre for Design at RMIT University, Victoria University, University of New South Wales	
249	Research on lifecycle fixed resources and exhausted carbon dioxide by buildings in Japan	Noboru Urushizaki, Takeo Kamioka, Chiaki Kaneko & Sato	1994	Proceedings of the CIB conference on buildings and the environment.	
250	RheinzinK, Titanium Zinc - Environmental Product Declaration	Institut Bauen und Umwelt -German Institute of Constructi	2005	Declaration number: AUB-RHE-11105-E	
251	Rockwool environmental report: The wind of change	Rockwool limited	1997	Rockwool Limited	
252	RT Environmental declaration Cold rolled steel sheet and coils	Rautaruukki Oyj; www.ruukki.com	2007	Rautaruukki Oyj; www.ruukki.com	
253	RT Environmental declaration Colour coated steel sheets and coils	Rautaruukki Oyj; www.ruukki.com	2007	Rautaruukki Oyj; www.ruukki.com	
254	RT Environmental declaration Metal coated steel sheet and coils	Rautaruukki Oyj; www.ruukki.com	2007	Rautaruukki Oyj; www.ruukki.com	
255	RT Environmental declaration Ruukki's structural hollow sections, steel pipe piles and steel sections	Rautaruukki Oyj; www.ruukki.com	2007	Rautaruukki Oyj; www.ruukki.com	
256	RT Environmental Declaration: External wall element system (Nordicon)	Rautaruukki Oyj; www.ruukki.com	2007	Rautaruukki Oyj; www.ruukki.com	
257	RT Environmental Declaration: Light-weight Sandwich Element System (Panel 3Lock)	Rautaruukki Oyj; www.ruukki.com	2007	Rautaruukki Oyj; www.ruukki.com	
258	RT Environmental Declaration: Rautaruukki Oyj, Hot-rolled frames and bridge structures	Rautaruukki Oyj; www.ruukki.com	2007	Rautaruukki Oyj; www.ruukki.com	
259	RT Environmental Declaration: Rautaruukki Oyj, Roofing sheets and façade claddings (paint coated)	Rautaruukki Oyj; www.ruukki.com	2007	Rautaruukki Oyj; www.ruukki.com	
260	RT Environmental Declaration: Rautaruukki Oyj, Roofing sheets, façade claddings, purlins, framings and co	Rautaruukki Oyj; www.ruukki.com	2007	Rautaruukki Oyj; www.ruukki.com	
261	RT-Environmental declaration Hot rolled steel plates, sheet and coils	Rautaruukki Oyj; www.ruukki.com	2007	Rautaruukki Oyj; www.ruukki.com	
262	Sandstone Quarrying and Processing: A Life-Cycle Inventory	University of Tennessee	2008	University of Tennessee	
263	Sikament 160 Technical data Sheet	Sika Limited	2005	Sika Limited	
264	Sikkens Cetol BL 21 cradle to gate data	Imperial College Life Cycle Assessment Group	2003	Akzo Nobel Specialist Coatings	
265	Sikkens Cetol BL 31 cradle to gate data	Imperial College Life Cycle Assessment Group	2003	Akzo Nobel Specialist Coatings	
266	Sikkens Cetol BL opaque cradle to gate data	Imperial College Life Cycle Assessment Group	2003	Akzo Nobel Specialist Coatings	
267	Sikkens Cetol BL Primer cradle to gate data	Imperial College Life Cycle Assessment Group	2003	Akzo Nobel Specialist Coatings	
268	Sikkens Cetol WF 955 cradle to gate date	Imperial College Life Cycle Assessment Group	2003	Akzo Nobel Specialist Coatings	
269	Sikkens Cetol WP 560 cradle to gate data	Imperial College Life Cycle Assessment Group	2003	Akzo Nobel Specialist Coatings	
270	Sikkens Rubbol WF 380 cradle to gate data	Imperial College Life Cycle Assessment Group	2003	Akzo Nobel Specialist Coatings	
271	Solarwall, Colorcoat assessed cladding system - Environmental Product Declaration	Corus	2002	CA Building Products	
272	Suspension polymerised PVC LCI Data Summary	I Boustead	1999	APME, Association of Plastics Manufacturers in Europe	
273	Suspension polymerised PVC LCI Data Summary in Excel	I Boustead	1999	APME, Association of Plastics Manufacturers in Europe	
274	Sustainability analysis of window frames	M Asif, T Muneer & J Kubie	2005	Napier university	
275	Sustainable homes: Embodied energy in residential property development, A guide for registered social lan	Sustainable homes	1999	Sustainable homes, http://www.sustainablehomes.co.uk	
276	Tecu, Copper Strips and Copper Alloys - Environmental Product Declaration	Institut Bauen und Umwelt -German Institute of Constructi	2007	Declaration number: AUB-KME-30807-E	
277	Textile floor covering (PA 6) - Environmental Product Declaration	Institut Bauen und Umwelt -German Institute of Constructi	2009	Declaration number: EPD-GUT-2009211-E	
278	Textile floor covering (PA 6), backing of textile fabrics - Environmental Product Declaration	Institut Bauen und Umwelt -German Institute of Constructi	2009	Declaration number: EPD-GUT-2009511-E	
279	Textile floor covering (PA 6.6) - Environmental Product Declaration	Institut Bauen und Umwelt -German Institute of Constructi	2009	Declaration number: EPD-GUT-2009311-E	
280	Textile mass balances and product life cycles; Ref S5471	British Textile Technology Group	1999	British Textile Technology Group	
281	The Energy Embodied in Building Materials - updated New Zealand coefficients and their significance	George Baird, Andrew Alcorn, Phil Haslam	1997	Centre for Building Performance Research, Victoria University of Wellington	
282	The environmental impacts of the production of hemp and flax textile yarn	Hayo M.G. van der Werf, Lea Turunen	2008	industrial crops and products 2 7 (2 0 0 8) 1–10	
283	The European Steel Industry and Climate Change	EUROFER, European Confederation of Iron and Steel Ind	2000	EUROFER, European Confederation of Iron and Steel Industries	
284	The Finnish metals industry and the environment	Jyri Seppala, Sirkka Koskela, Matti Melanen, Matti Palperi	2002	Resources conservation and recycling (Journal), Elsevier	
285	The Future of the European Aluminium Industry: A MARKAL Energy and Material Flow Analysis	D J Gielen	1998	ECN-Policy Studies	
286	The Life Cycle of copper, its co-products and by-products	Robert U Ayres, Leslie W Ayres and ingrid Rade	2002	International institute for Environment and Development	
287	The Lifecycle assessment of Italian clay brick products	Mariachiara Torricelli	2005	Unknown	
288	The measure of our sustainability, Report of the world steel industry 2004	International Iron and Steel Institute	2003	IISI, International Iron and Steel Institute	
289	Thermoformed, Expanded Polystyrene LCI Data Summary	I Boustead	2005	APME, Association of Plastics Manufacturers in Europe	
290	Thermoformed, Expanded Polystyrene LCI Data Summary in Excel format	I Boustead	2005	APME, Association of Plastics Manufacturers in Europe	
291	Timber as a building material - An environmental comparison against synthetic building materials	Phil Townsend and Chris Wagner	2002	National Association of Forest Industries Ltd	
292	Tonality, ceramic cladding elements - Environmental Product Declaration	Institut Bauen und Umwelt -German Institute of Constructi	2009	Declaration number: EPD-CRE-2009111-E	
293	Towards the holistic assessment of building performance based on an integrated systems approach	Stephane Citherlet	2001	Swiss federal institute of technology	
294	Uncoated wood-free fine paper - Environmental Product Declaration	Asia Pacific Resources International Holdings Ltd.	2008		
295	What LCA can tell us about the cement industry	Steven B. Young, Shannon Turnbul & Andrea Russell	2002	Five winds international; World business council for sustainable development	
296	Window and advanced glazing systems life cycle assessment	Stephane Citerlet, Francesca Di Gulielmo & Jean-Bernard	2000	Energy & Buildings 32 pg 225-234	
297	Wood based building materials and atmospheric carbon emissions	Andrew H. Buchanan & S. Bry Levine	1999	Environmental Science & Policy 2 (1999) 427±437	
298	World steel life cycle inventory - IISI methodology report	IISI - International Iron & Steel Institute	2000	IISI - International Iron & Steel Institute	
299	Ytong, Autoclaved Aerated Concrete (AAC) - Environmental Product Declaration	Institut Bauen und Umwelt -German Institute of Constructi	2005	Declaration number: AUB-XEL-11005-E	



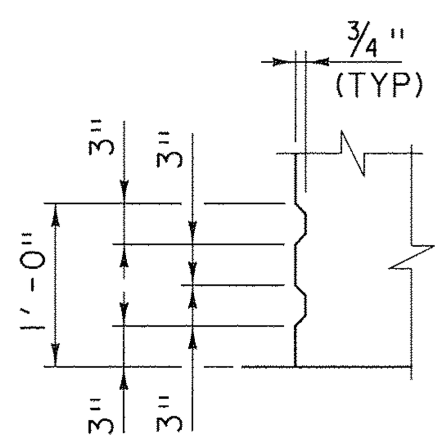
RAILING & END WALL APPROACH



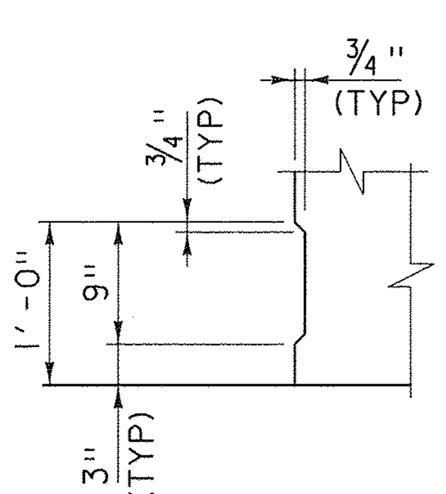
RAIL TYPICAL SECTION

NOTES:

1. ALL WORK AND MATERIALS SHALL CONFORM TO SECTION 525.
2. PRIOR TO GALVANIZING THE ASSEMBLED POST, GRIND ALL EDGES TO A MINIMUM RADIUS OF 1/16".
3. ALL POSTS SHALL BE SET NORMAL TO GRADE.
4. SECTIONS OF RAIL TUBE SHALL BE ATTACHED TO A MINIMUM OF TWO BRIDGE POSTS AND PREFERABLY TO AT LEAST 4 POSTS.
5. HOLES IN RAILS FOR TUBE ATTACHMENT MAY BE FIELD-DRILLED. HOLES SHALL BE COATED WITH AN APPROVED ZINC-RICH PAINT PRIOR TO INSTALLATION.
6. BOLTS SHALL BE TORQUED SNUG TIGHT (APPROXIMATELY 100 FT-LB).
7. RAIL TUBES SHALL BE ATTACHED USING 3/4" FULL DIAMETER BODY ASTM A 449 (TYPE 1) ROUND HEAD BOLTS INSERTED THROUGH THE FACE OF THE TUBE.
8. SEE STANDARD DRAWING G-1 FOR DETAILS OF DELINEATORS. A DELINEATOR SHALL BE INSTALLED AT 30 FOOT SPACING OR THE NEAREST POST. WHITE IS TO BE INSTALLED ON THE DRIVER'S RIGHT. FOR ONE WAY BRIDGES, YELLOW IS TO BE INSTALLED ON THE DRIVER'S LEFT. PAYMENT FOR DELINEATORS SHALL BE INCIDENTAL TO OTHER ITEMS.
9. AESTHETIC TREATMENT TYPE SHALL BE APPLIED AS SPECIFIED IN THE CONTRACT PLANS. IF NONE IS SPECIFIED IT SHALL NOT BE USED. AESTHETIC TREATMENT DETAILED ON THIS SHEET MAY ALSO BE APPLIED ON THE FASCIA SIDE OF THE RAIL, IF SPECIFIED IN THE CONTRACT PLANS.
10. BRIDGE RAILING SHALL HAVE A RUBBED FINISH IN ACCORDANCE WITH SECTION 501.
11. THIS RAILING MEETS THE REQUIREMENTS FOR A NCHRP REPORT 350 TL-4 SERVICE LEVEL.

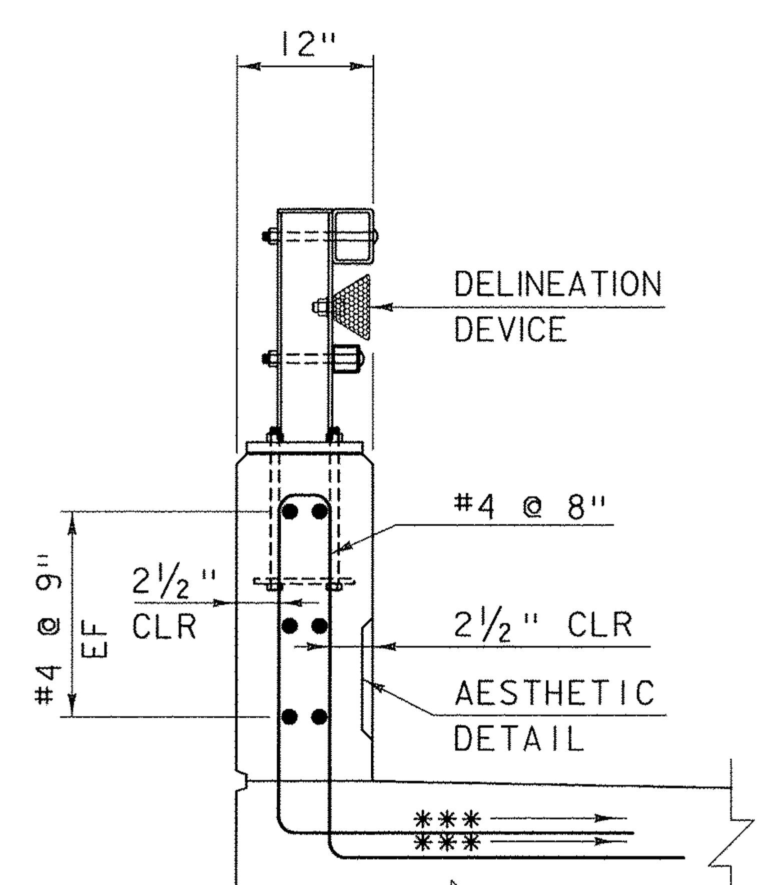


AESTHETIC DETAIL A

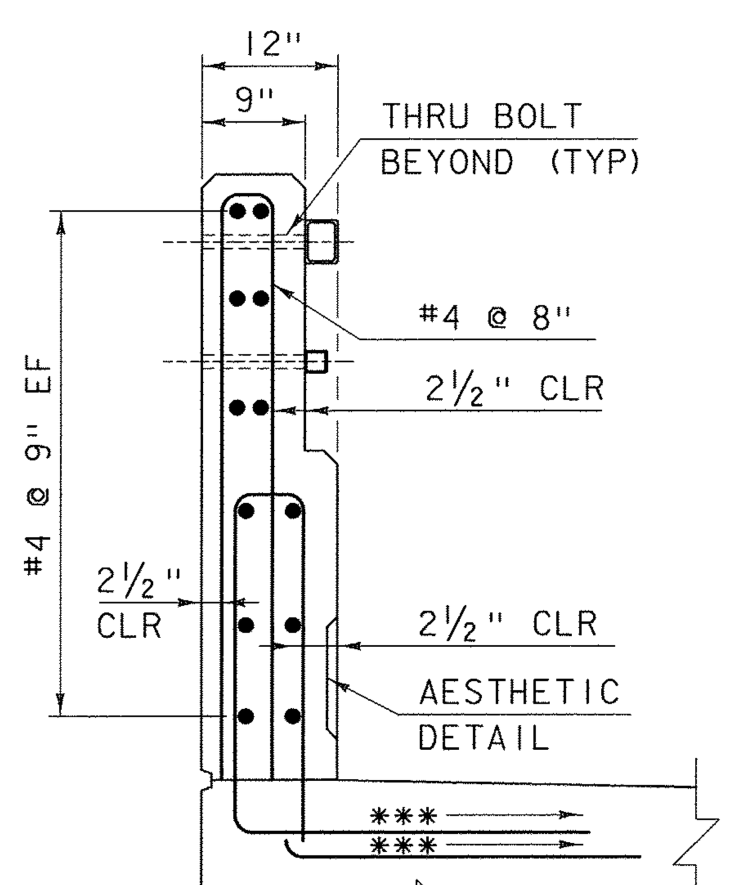


AESTHETIC DETAIL B

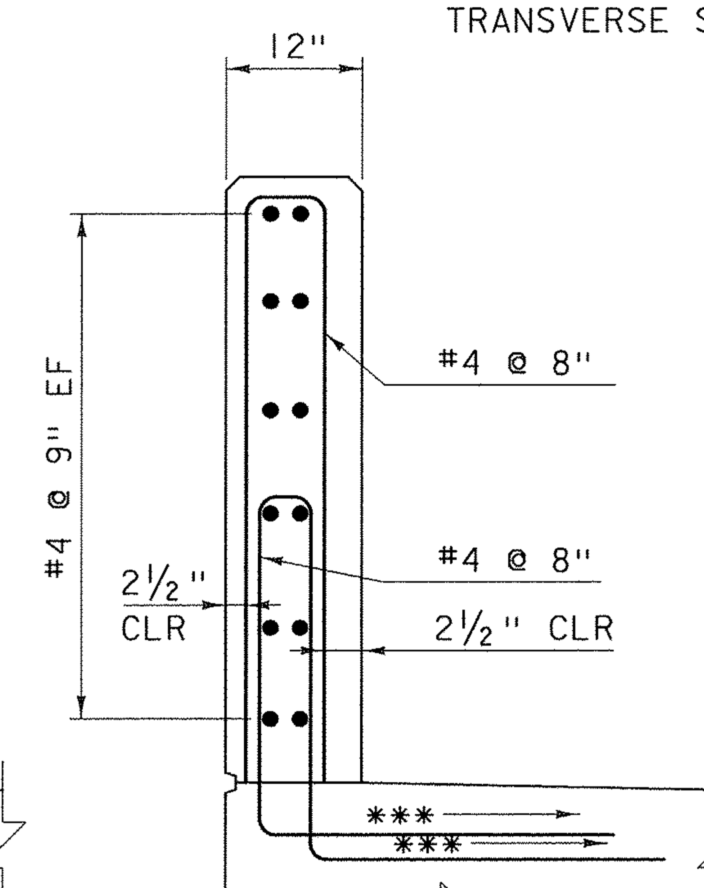
NOTE:
EF = EACH FACE
3" CLEAR, UNLESS OTHERWISE SPECIFIED ON THE PLANS.
2'-2" BAR LAP UNLESS OTHERWISE SPECIFIED ON THE PLANS.
*** MATCH SLOPE OF NEAREST TRANSVERSE STEEL



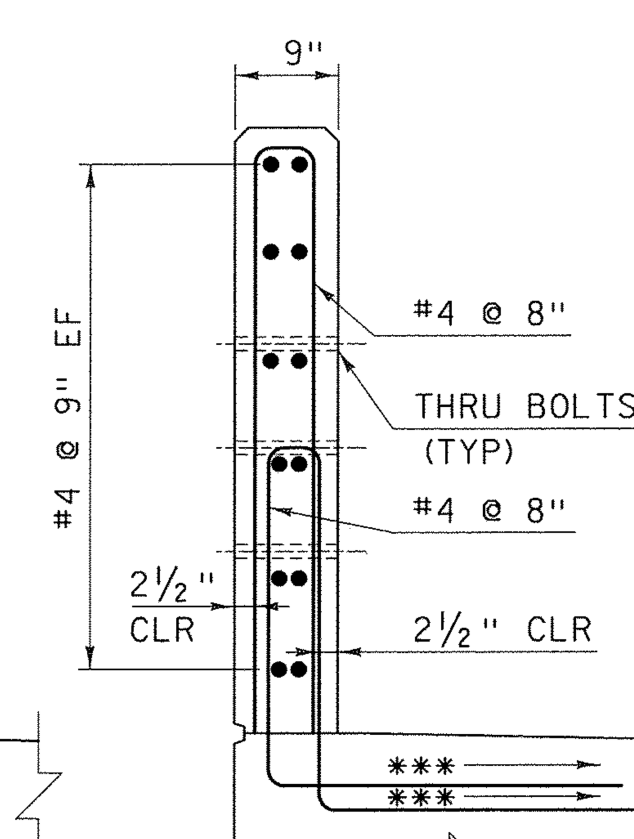
SECTION A-A



SECTION B-B



SECTION C-C



SECTION D-D

OTHER STDS. REQUIRED: **G-1**

REVISIONS AND CORRECTIONS

AUGUST 22, 2012 - ORIGINAL APPROVAL

APPROVED

Wm. Michael Hedges
STRUCTURES ENGINEER

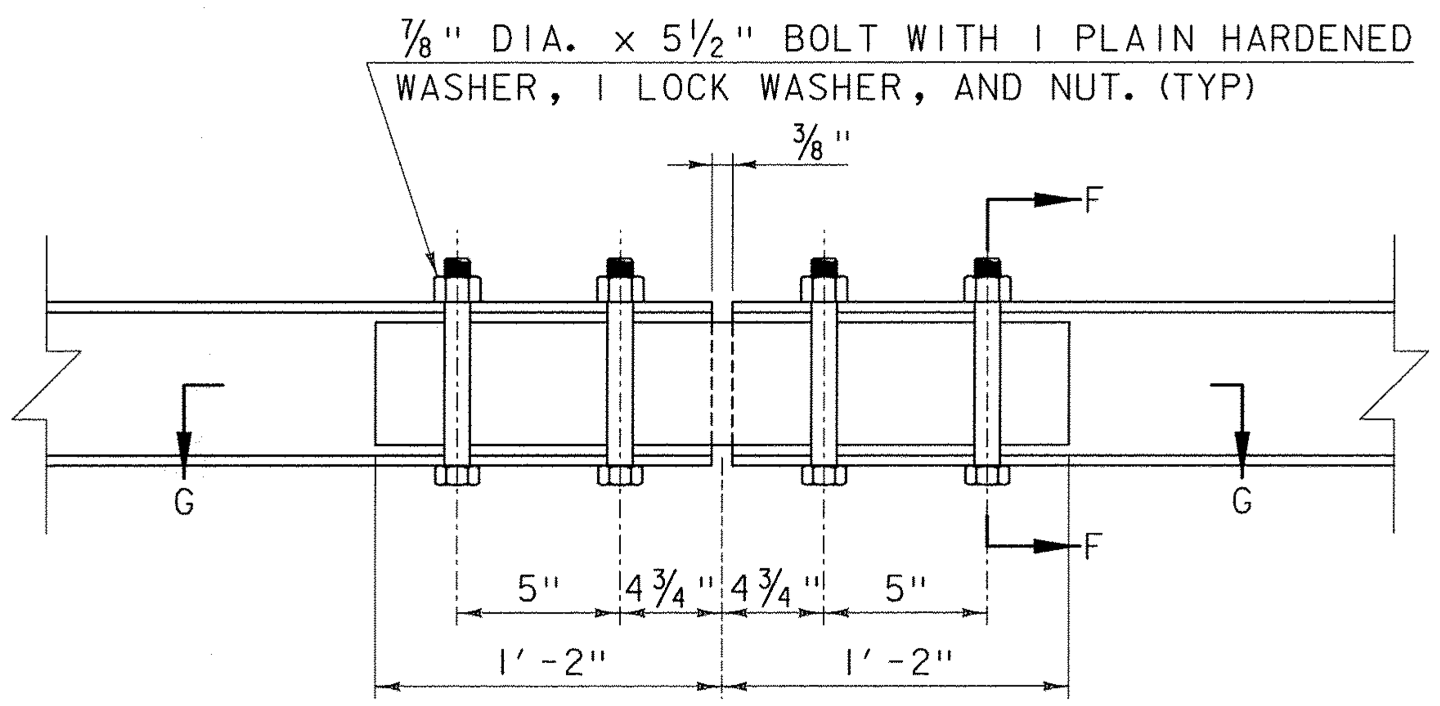
Richard Tetreault
DIRECTOR OF PROGRAM DEVELOPMENT

Mark D. Richter
FEDERAL HIGHWAY ADMINISTRATION

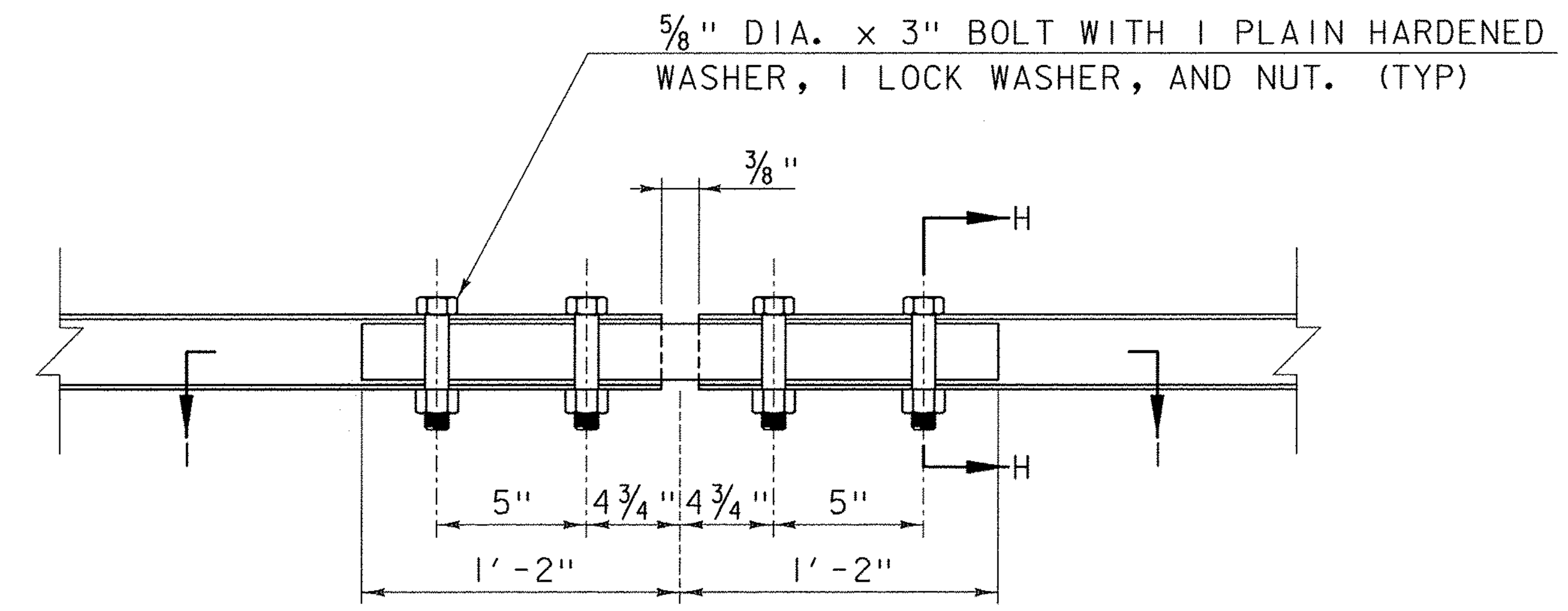
BRIDGE RAILING, GALVANIZED STEEL TUBING / CONCRETE COMBINATION

VERMONT AGENCY OF TRANSPORTATION

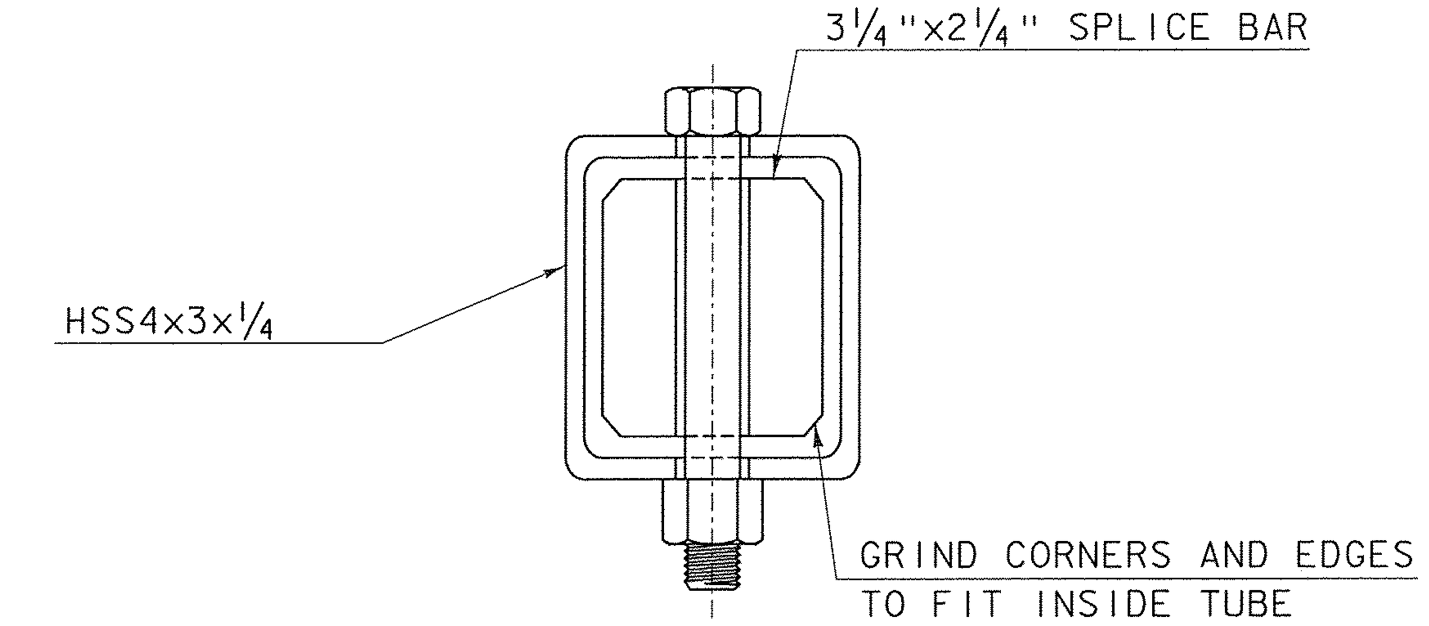
STANDARD S-352A



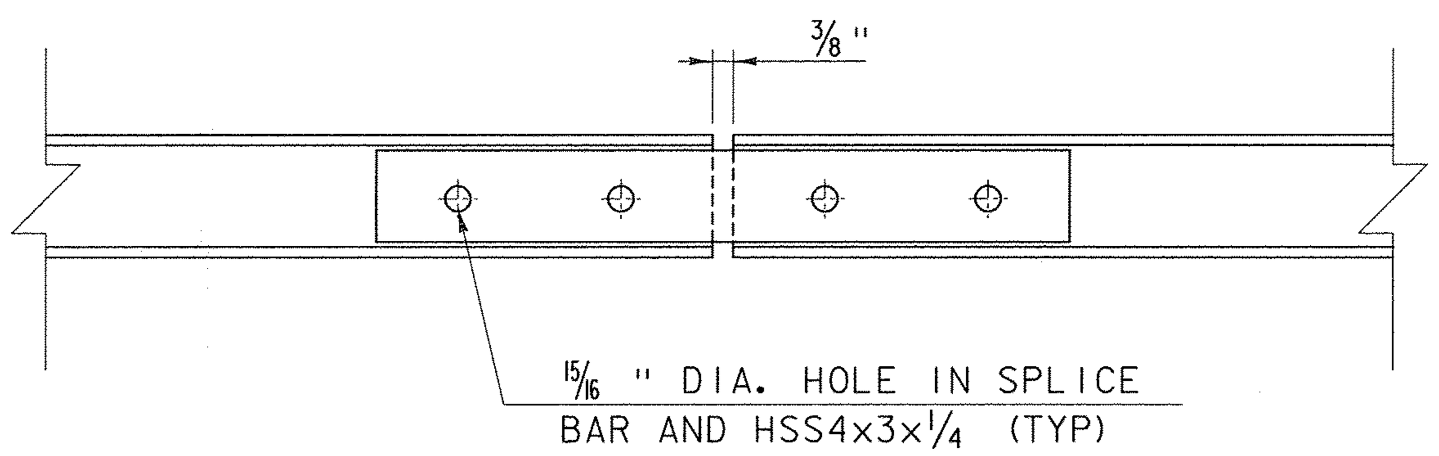
TOP RAIL FIXED SPLICE DETAIL



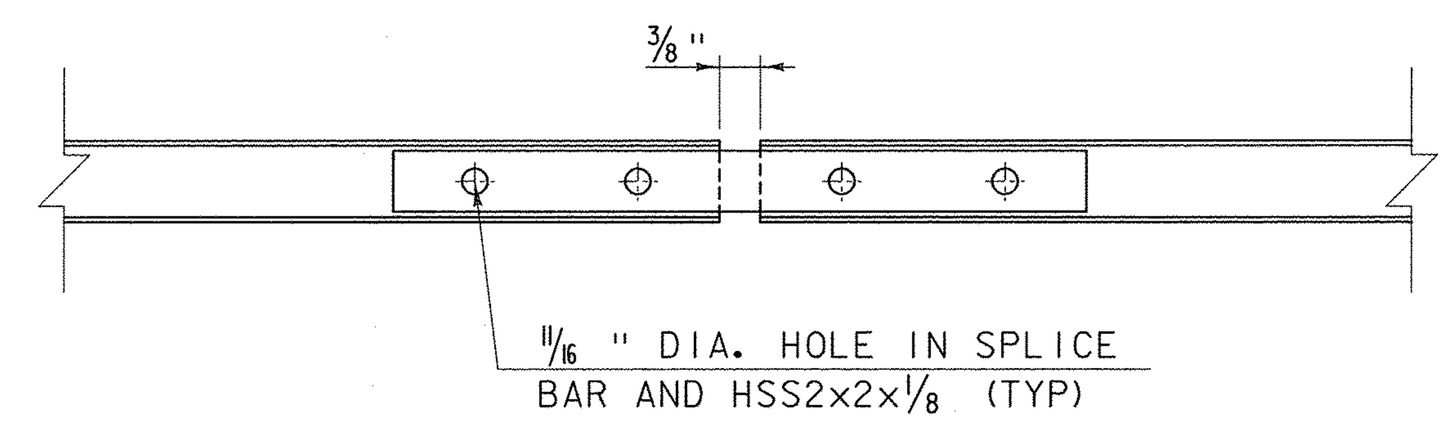
BOTTOM RAIL FIXED SPLICE DETAIL



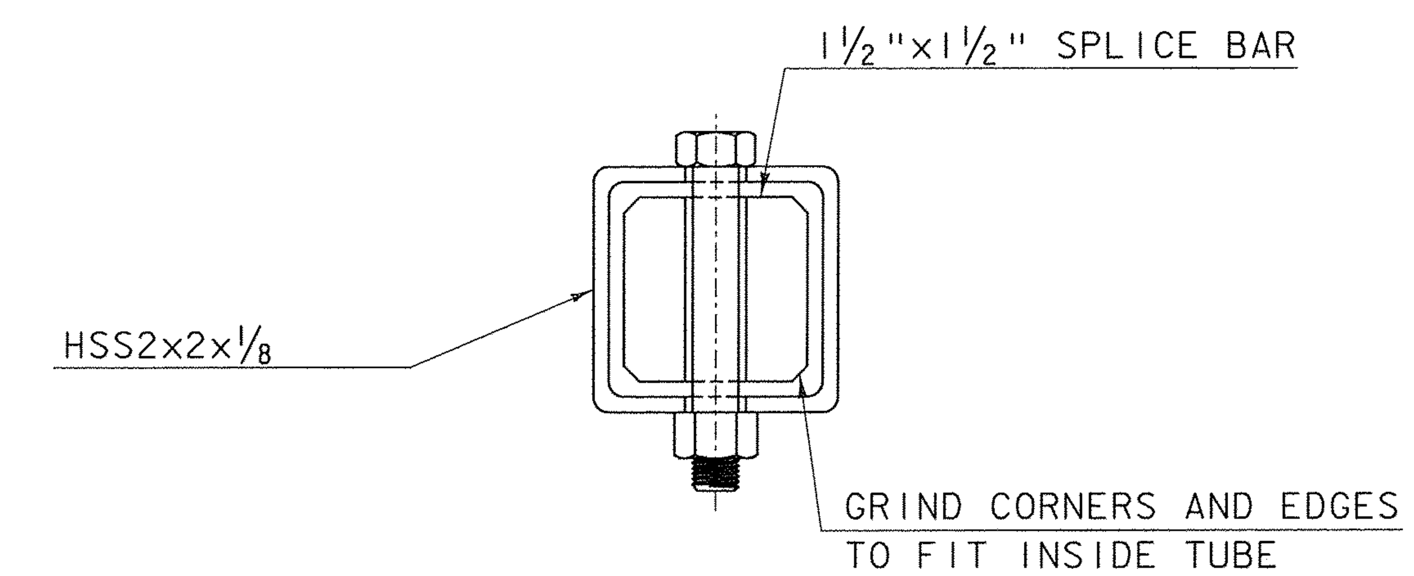
SECTION F-F



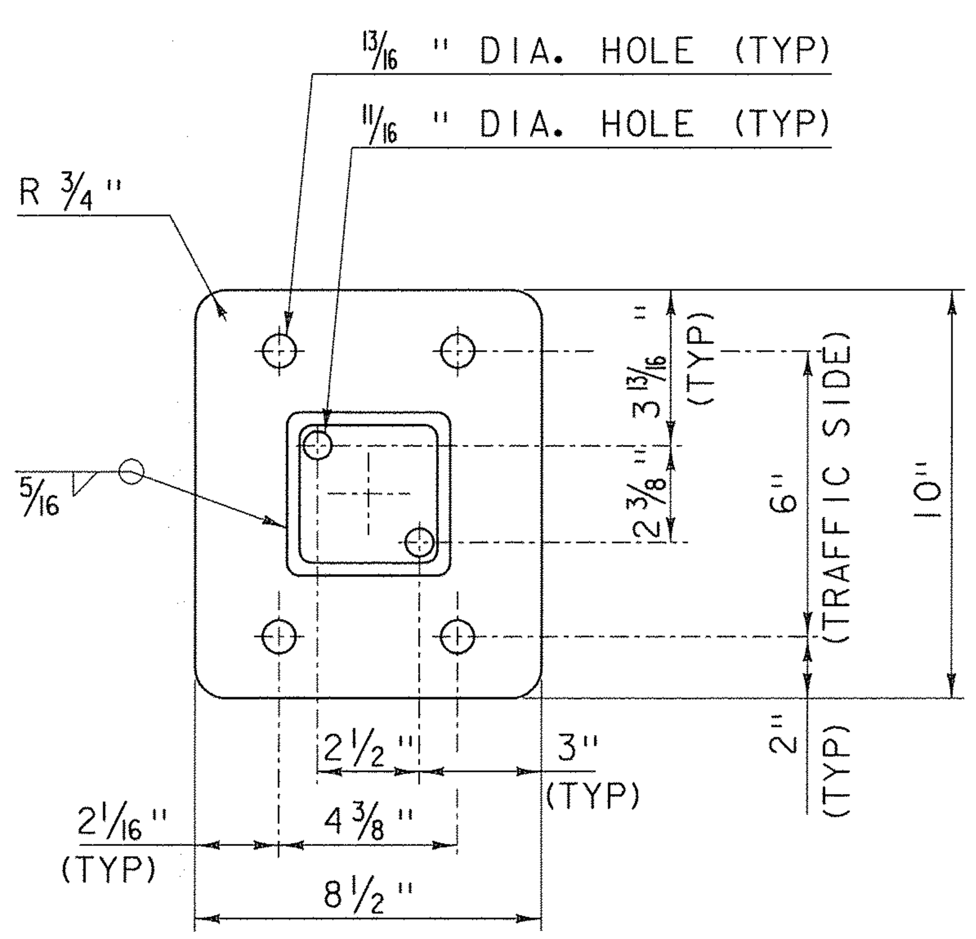
SECTION G-G



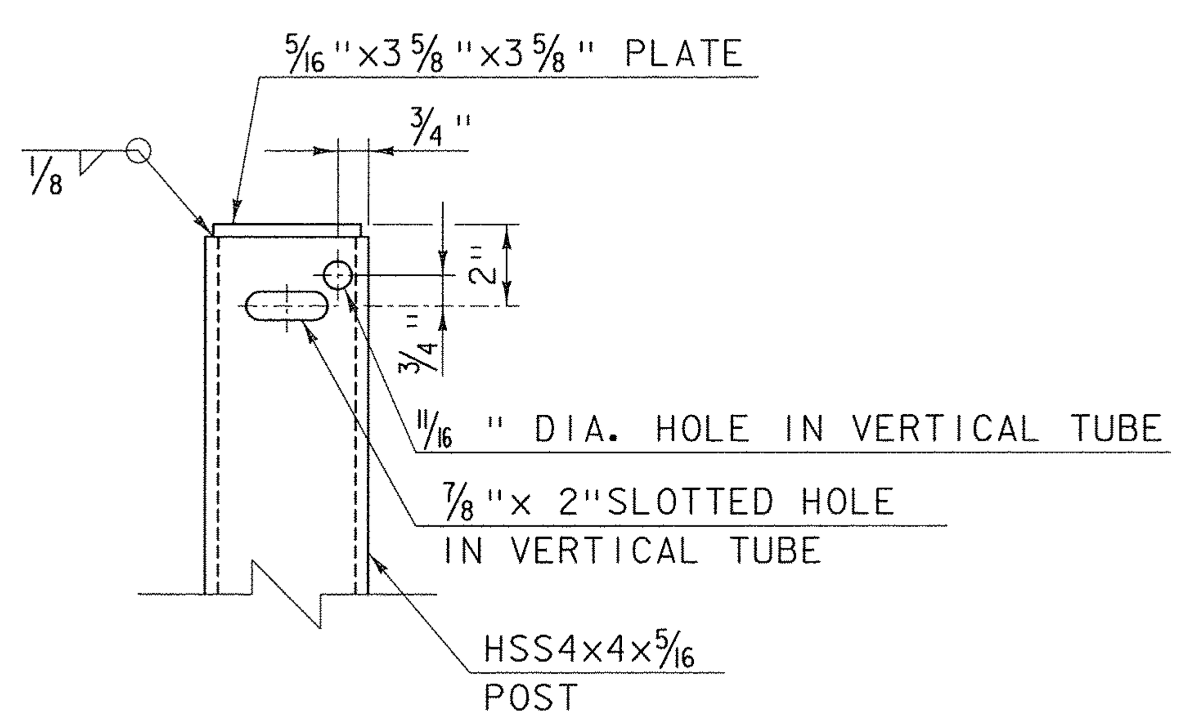
SECTION I-I



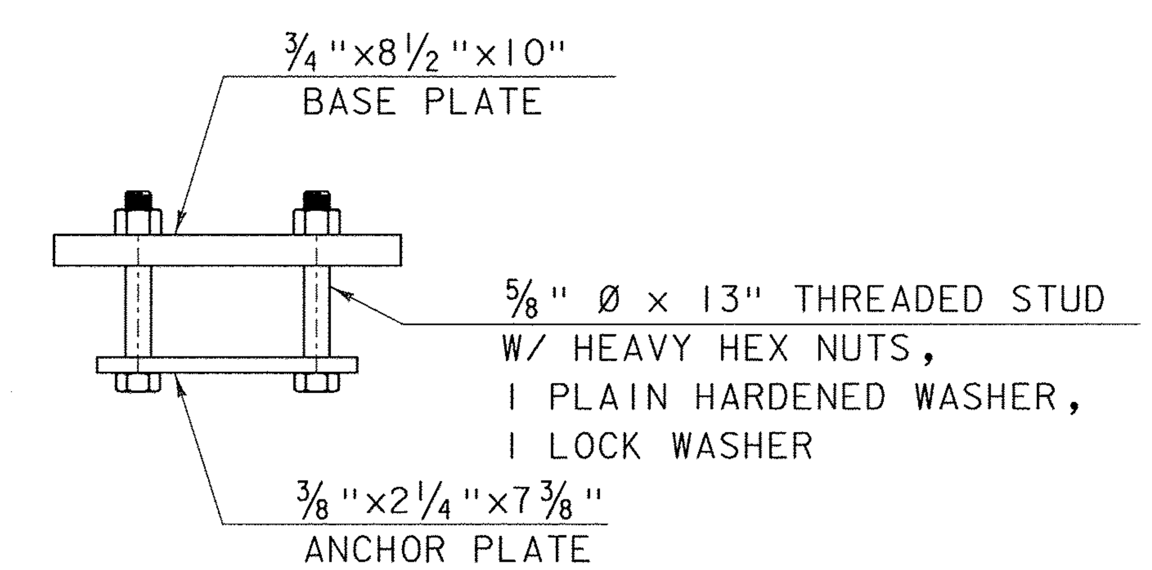
SECTION H-H



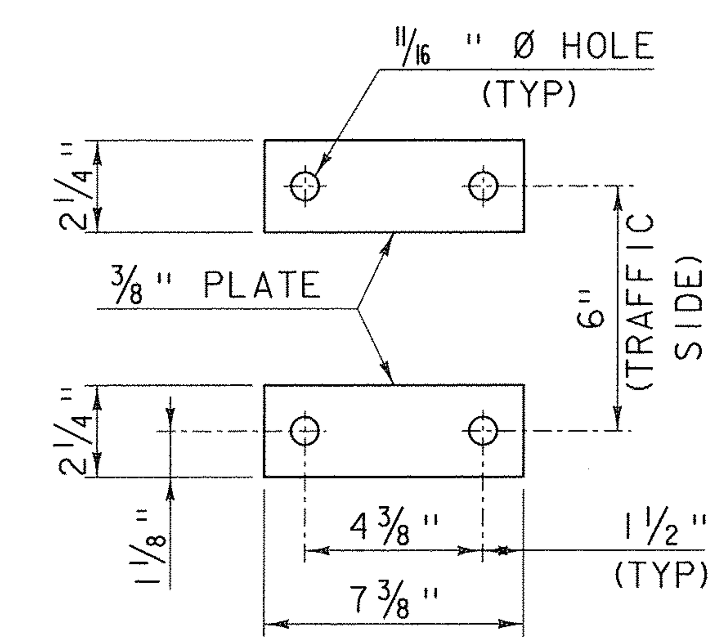
BASE PLATE



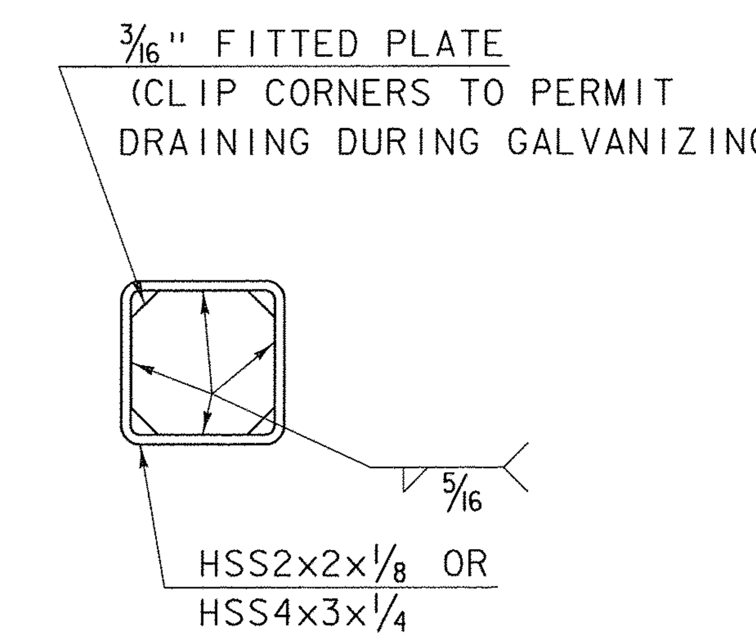
VERTICAL TUBE DETAIL
(FRONT VIEW)



RAIL POST ANCHORAGE



ANCHOR PLATES



END OF RAIL DETAIL

OTHER STDS. REQUIRED: **G-1**

REVISIONS AND CORRECTIONS

AUGUST 22, 2012 - ORIGINAL APPROVAL

APPROVED

Wm. Michael Hedges
STRUCTURES ENGINEER

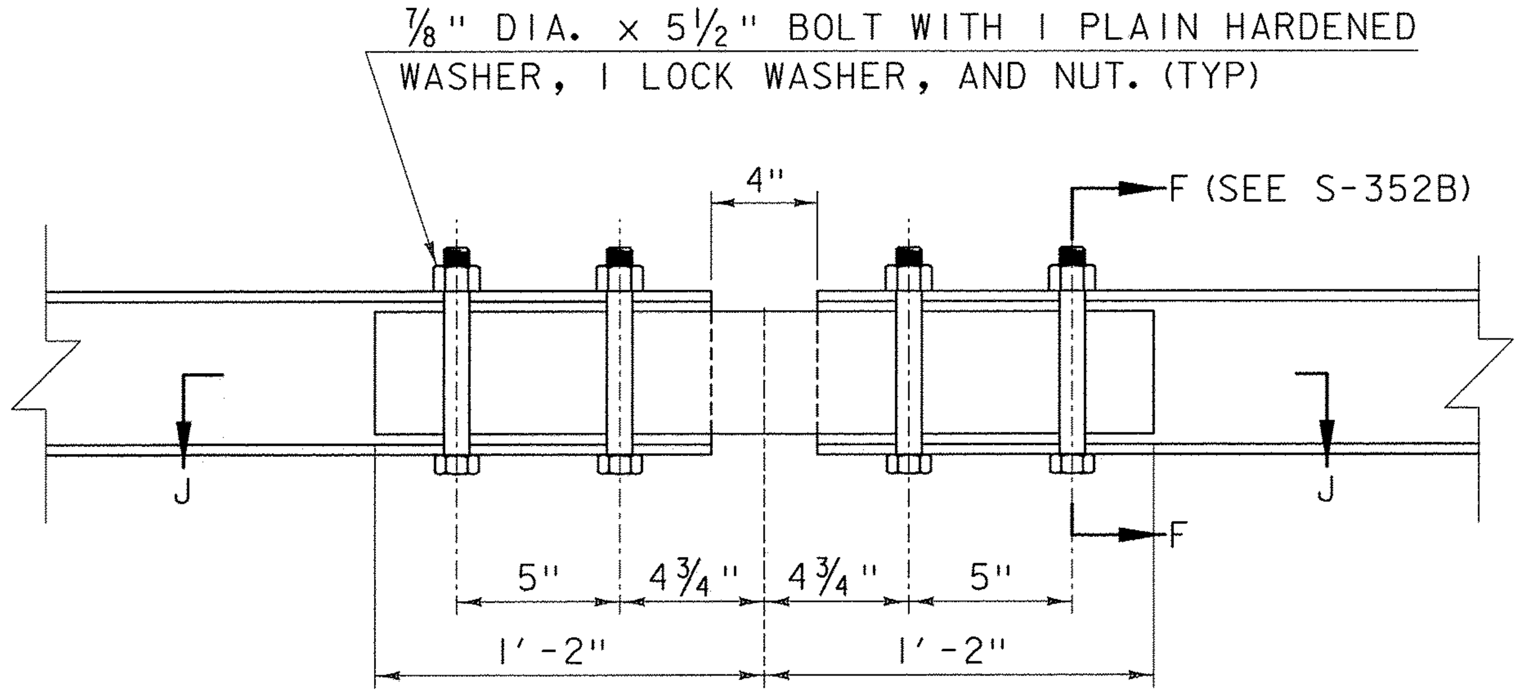
Richard Tetreault
DIRECTOR OF PROGRAM DEVELOPMENT

Mark D. Richter
FEDERAL HIGHWAY ADMINISTRATION

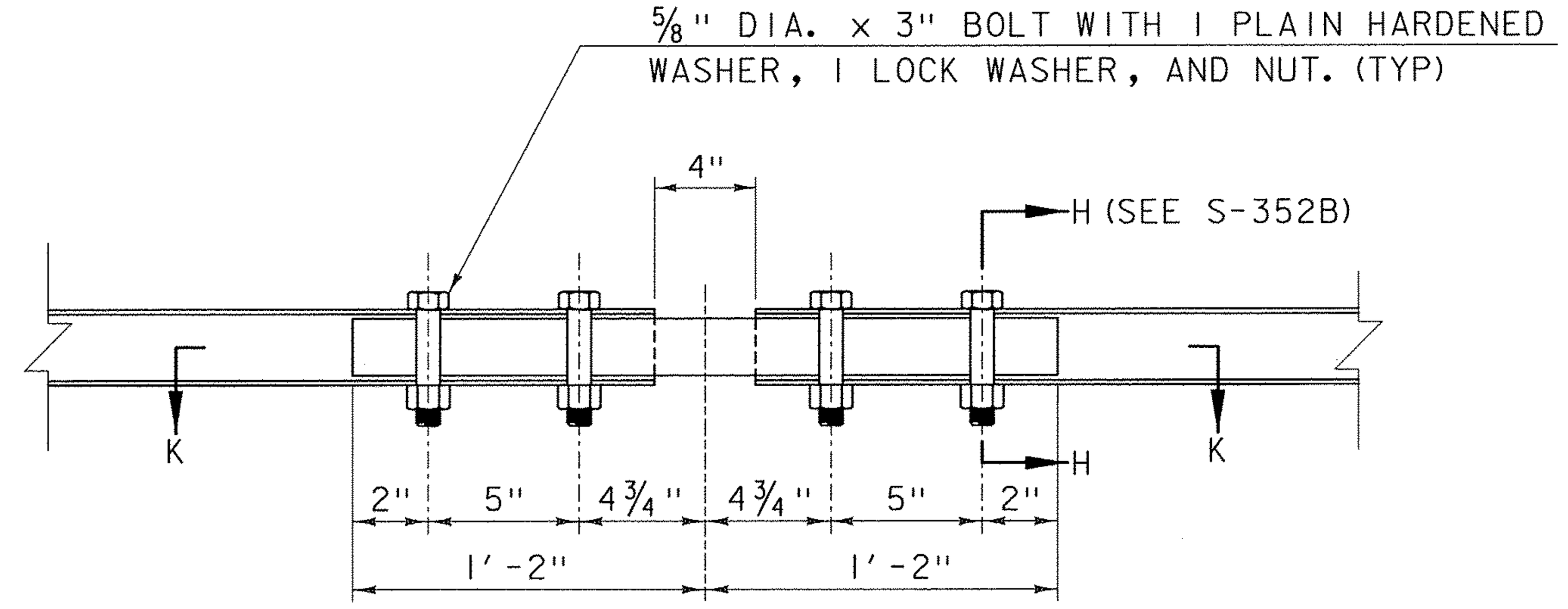
BRIDGE RAILING, GALVANIZED STEEL TUBING / CONCRETE COMBINATION

VERMONT AGENCY OF TRANSPORTATION

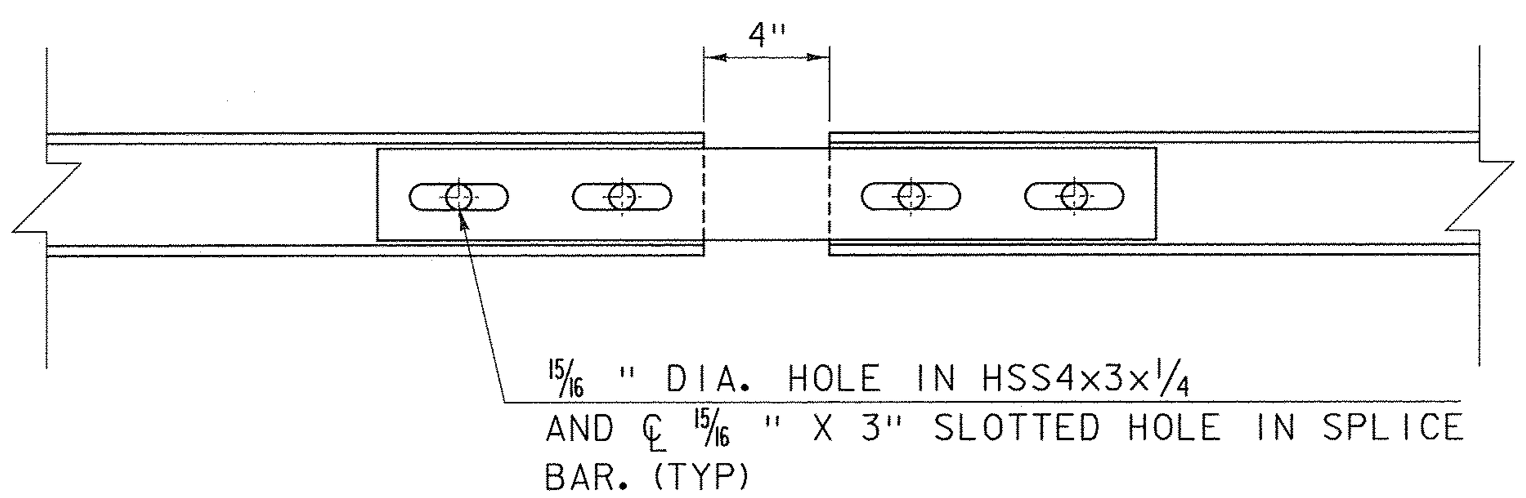
STANDARD S-352B



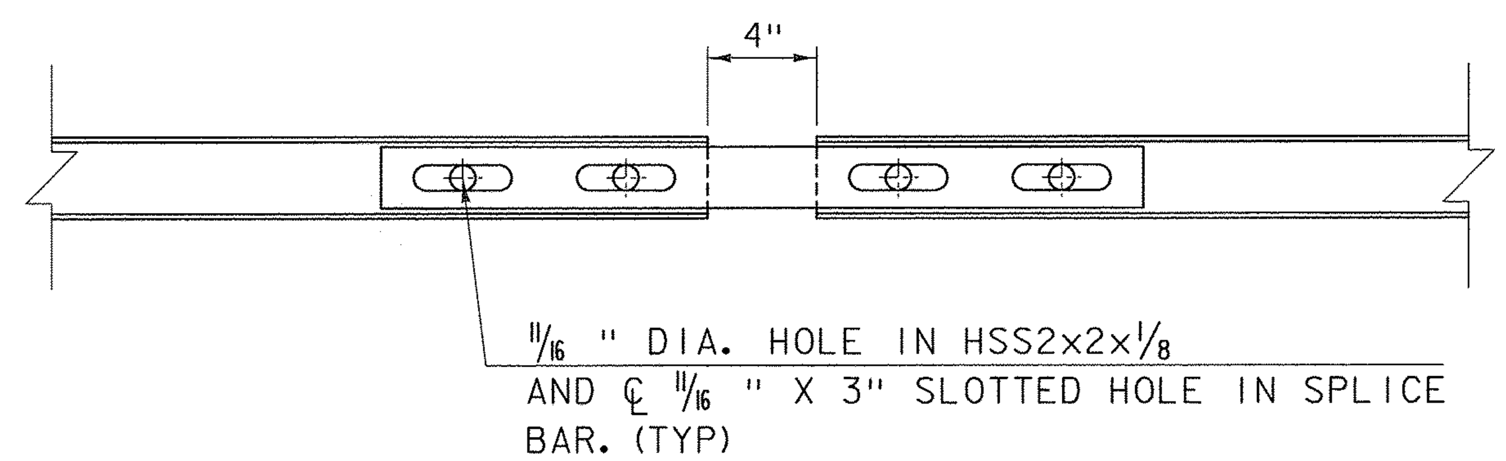
TOP RAIL EXPANSION SPLICE DETAIL



BOTTOM RAIL EXPANSION SPLICE DETAIL



SECTION J-J



SECTION K-K

OTHER STDS. REQUIRED: G-1

REVISIONS AND CORRECTIONS

AUGUST 22, 2012 - ORIGINAL APPROVAL

APPROVED

STRUCTURES ENGINEER

DIRECTOR OF PROGRAM DEVELOPMENT

FEDERAL HIGHWAY ADMINISTRATION

BRIDGE RAILING, GALVANIZED STEEL TUBING / CONCRETE COMBINATION

VERMONT AGENCY OF TRANSPORTATION

STANDARD

S-352C